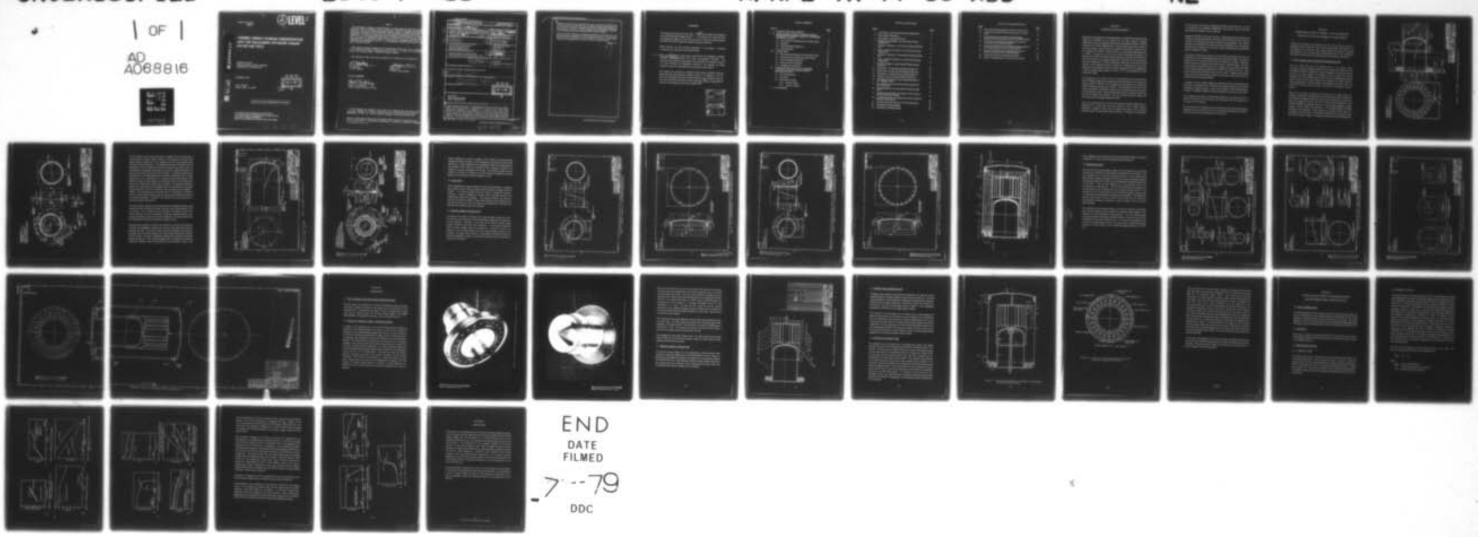
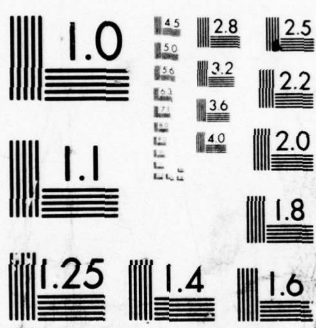
AD-A068 816 XEROX CORP/ELECTRO-OPTICAL SYSTEMS PASADENA CALIF F/G 20/12
THERMAL ENERGY STORAGE DEMONSTRATION UNIT FOR VUILLEUMIER CRYOG--ETC(U)
DEC 78 R RICHTER F33615-75-C-2045
UNCLASSIFIED 2340-F-ADD AFAPL-TR-77-65-ADD NL

1 OF 1
AD
A068816



END
DATE
FILMED
7-79
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFAPL-TR-77-65
SUPP 1

② LEVEL II

AD A068816

THERMAL ENERGY STORAGE DEMONSTRATION UNIT FOR VUILLEUMIER CRYOGENIC COOLER (HI-CAP UNIT NO.2)

ROBERT RICHTER
XEROX ELECTRO-OPITCAL SYSTEMS
PASADENA, CALIFORNIA 91107

DECEMBER 1978

FINAL REPORT
February 1978 – July 1978

Approved for public release; distribution unlimited

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

79 05 15 053

NOTICE

When Government drawings, specifications, or other data are used for any pur pose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor a obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licen sing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Information Office (OI) and is releasabl to the National Technical Information Service (NTIS). At NTIS, it will be avai able to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

E.T.MAHEFKEY
Project Engineer

JOSEPH WISE
Technical Area Manager

FOR THE COMMANDER

ROBERT R. BARTHELEMY
Chief, Energy Conversion Branch

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFAPL/POE *, W-PAFB, OH 45433 to help us maintain a current mailing list".*

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

63428F

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 18 AFAPL-TR-77-65-S[redacted] ADD	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 THERMAL ENERGY STORAGE DEMONSTRATION UNIT FOR VUILLEUMIER CRYOGENIC COOLER (HI-CAP UNIT [redacted] Number 2). Addendum		5. TYPE OF REPORT & PERIOD COVERED 9 Final Report, 1 Feb[redacted] [redacted]-31 Jul[redacted]78
		6. PERFORMING ORG. REPORT NUMBER 2340-Final - Addendum
7. AUTHOR(s) 10 Robert Richter		8. CONTRACT OR GRANT NUMBER(s) 15 F33615-75-C-2045
9. PERFORMING ORGANIZATION NAME AND ADDRESS Xerox Electro-Optical Systems 300 North Halstead Street Pasadena, California 91107		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project No. 2126 Task No. 03 Work Unit No. 10
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Propulsion Laboratory/POE Wright-Patterson Air Force Base, Ohio 45433		12. REPORT DATE 11 Dec[redacted]78
		13. NUMBER OF PAGES 45
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 46p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

14 2340-F-ADD

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

16 2126 17 03

DDC
RECEIVED
MAY 21 1979
B

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Space Power
Thermal Energy Storage
Phase Change Material

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A second thermal energy unit for the High Capacity (Hi-Cap) Vuilleumier Cryogenic Cooler was built and tested. Incorporated into this unit were several design improvements consisting of the addition of a conduction heat transfer barrier between the radiation heat shield insulation and the mounting flange, modification of the O-ring seal of the insulation container, moving the hot cylinder-mounting flange interface, and changing the instrumentation. All design changes proved to be beneficial. The thermal losses that can be attributed to heat transfer through the

over

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

124 650 Gw

insulation were lowered by about 8W from those of the first Hi-Cap TES unit. The inclusion of the terminal ring into the flange and separating the flange from the hot cylinder resulted in a substantial cost saving in material and machining of the components. The three, 1/16-inch diameter Inconel sheathed K calibration thermocouples performed consistently during the entire test period.

The prime concern has been the discharge characteristic of the TES unit. Test data evaluation has indicated that the charging characteristic of the TES unit should be further investigated to obtain necessary information which will be required for the integration of the TES unit with the cryogenic cooler.

FOREWORD

The information presented in this repor[illegible] generated during the performance of the Thermal Energy Storage Demon[illegible] Unit contract, Air Force Contract No. F33615-75-C-2045. The work was ca[illegible]ried out in the Electro-Optical Systems Division of the Xerox Corporation (XEOS), Pasadena, California.

Robert Richter was the principal investigator of the program. Individual contributors were members of the XEOS Division.

This is an addendum to final report AFAPL-TR-77-65, "THERMAL ENERGY STORAGE DEMONSTRATION UNIT FOR VUILLEUMIER COOLER." The technical results which were presented in the final report are frequently referred to as they furnished the background material for the redesign and testing procedures which were undertaken during this phase of the program.

The program was sponsored by SAMSO/SZ under Project 21260310, "Thermal Energy Strorage Demonstration Program," with Mr. T. Mahefkey of the Air Force Aero Propulsion Laboratory (AFAPL/POE-2) acting as technical monitor. The work was performed during the period 1 February 1978 to 31 July 1978 with the draft of this addendum submitted in August 1978.

LIST OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

SECTION I
INTRODUCTION AND SUMMARY

During the second phase of a two-phase program, a single thermal energy storage (TES) unit, including the hot cylinder for the High Capacity Cryogenic Vuilleumier Cooler, was designed, fabricated, and performance tested. This TES unit was to be a direct replacement for the electrically heated hot cylinder of the Hi-Cap cooler. The TES unit was to supply the Vuilleumier cryogenic cooler for 18 minutes with 650W of thermal power at a nominal operating temperature of $1250^{o}F$. The goal was to limit, at the nominal operating temperature, the thermal losses from the thermal energy storage unit through the insulation to less than 5 percent of the design output power. Furthermore, the stored energy was to be released over a limited temperature range that would permit the hot cylinder of the Vuilleumier cooler to operate at a temperature of $1250 \pm 25^{o}F$. Based on the stated goals, the thermal energy storage unit had to be designed for a thermal energy storage capacity of 7.371×10^{5} J to be released over a $50^{o}F$ temperature range.

The performance test results of the first Hi-Cap TES unit verified that the thermal energy storage unit was supplying the specified power over a temperaure range of $1279^{o}F$ to $1227^{o}F$. The total losses were determined to be 154W at the nominal operating temperature of $1250^{o}F$. Of these losses, a total of 113.4W could be attributed to conduction through the hot cylinder wall to the crankcase of the Vuilleumier cooler. The remaining 40.6W had to be considered losses from the TES unit through the insulation. Thus, the insulation losses were about 8.1W or 25 percent above the specified goal of 32.5W.

After the successful delivery of the first Hi-Cap thermal energy storage unit, the production of a second TES unit was initiated, so that a High Capacity Vuilleumier Cryogenic Cooler could be tested with both its how cylinders operating under the same power input conditions. The goal of the additional effort, however, was not only to produce an identical Hi-Cap TES unit, but also to incorporate some desirable modifications that became evident during the fabrication and testing of the first TES unit.

During the assembly of the first TES unit a modification had to be made to the insulation container as described in the final report (AFAPL-TR-77-65). This fix resulted in an unsatisfactory though workable O-ring seal design. The insulation container of the second Hi-Cap TES unit has been redesigned with an O-ring seal that permits the closing of the container without requiring special precautions against damaging the O-ring.

The analysis of the thermal losses in the first TES unit indicated that heat was conducted into the mounting flange along the radiation heat shield. The thermal insulation of the second Hi-Cap TES unit was modified to include a conduction barrier between the radiation heat shield and the mounting flange. The tests performed on the second TES unit seem to indicate that the total thermal losses at the nominal operating temperature of 1250^{o}F are 146W for the unit. These losses are 8W below the losses of the first Hi-Cap TES. It appears that the goal of only 5 percent thermal losses through the insulation has been achieved by the modification of the insulation design.

A change in the hot cylinder design was undertaken which was dictated by the high cost of machining the hot cylinder and the terminal ring and by the limited availability of special material which became apparent when purchasing was initiated. This design change had not been anticipated at the outset of this task.

Some changes were made in the fabrication process of the Hi-Cap TES unit to make the casting of the TES material more predictable and the burping of the heat pipe more controllable.

The test results have indicated that the second Hi-Cap TES unit performs almost identically to the first unit, and that the structural modifications have had no detrimental effect on the performance of the TES unit.

SECTION II

DESIGN MODIFICATIONS OF THERMAL ENERGY STORAGE UNIT FOR HIGH CAPACITY VUILLEUMIER CRYOGENIC COOLER

During the fabrication and testing of the first Hi-Cap TES unit which is presented in report AFAPL-TR-77-65, several modifications in the design of the unit appeared to be desirable. These design changes were aimed at improving the assembly of the unit, lowering the manufacturing cost of the components, lowering the thermal losses, and improving the instrumentation and control.

2.1 HOT CYLINDER AND FLANGE WITH TERMINATION RING

The first Hi-Cap TES unit was designed around a hot cylinder, heater termination ring, and insulation container whose designs were taken over from the Hughes Aerospace Corporation. During the design of the first Hi-Cap TES unit, only two basic changes in the design of the hot cylinder were deemed necessary, one for maintaining stress levels which were considered safe and the other to insure vacuum tight sealing of the radiation heat shield insulation. The plate thickness of the hot cylinder was increased to a nominal 0.250 inch and the 5/16-inch bolt holes were made to end blind in the flange as shown in Figure 1.

When the hot cylinder was placed for machining, only a single vendor was willing to machine the relatively large Inconel forging which had a diameter of 8-1/2 inches and weighed 150 pounds. Furthermore, only one source was able to supply the forging from stock at that time. Based on these experiences in the limited availability of material and scarcity of machining capability, a design change in the hot cylinder was indicated. In this original design, the heater termination ring required a 9-inch diameter 1-inch-thick Inconel plate for machining from which about 7-1/2 inches of material had to be removed from the center as shown in Figure 2. During the evaluation of the requirements for

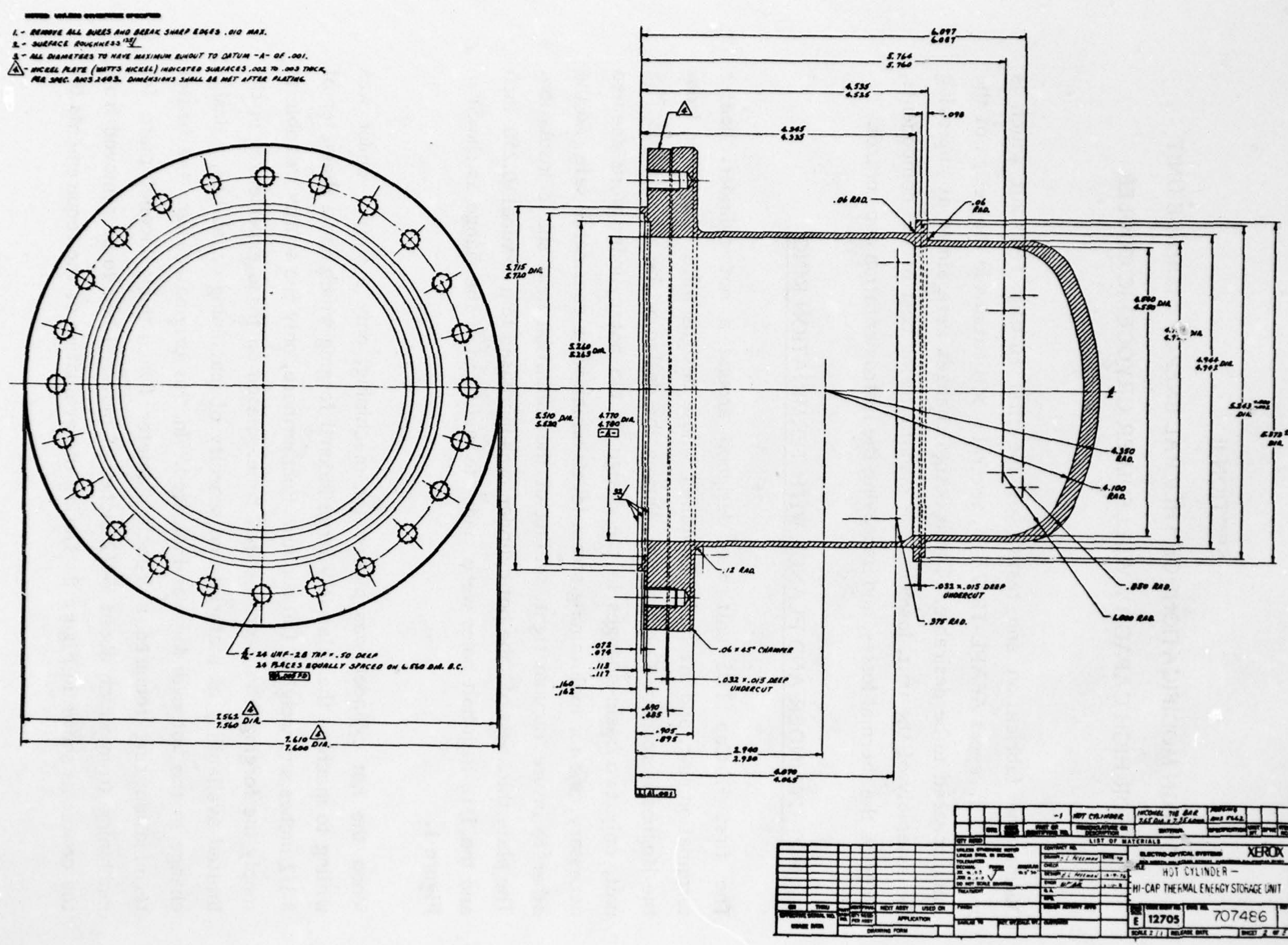


Figure 1. Hot Cylinder - Hi-Cap Thermal Energy Storage Unit

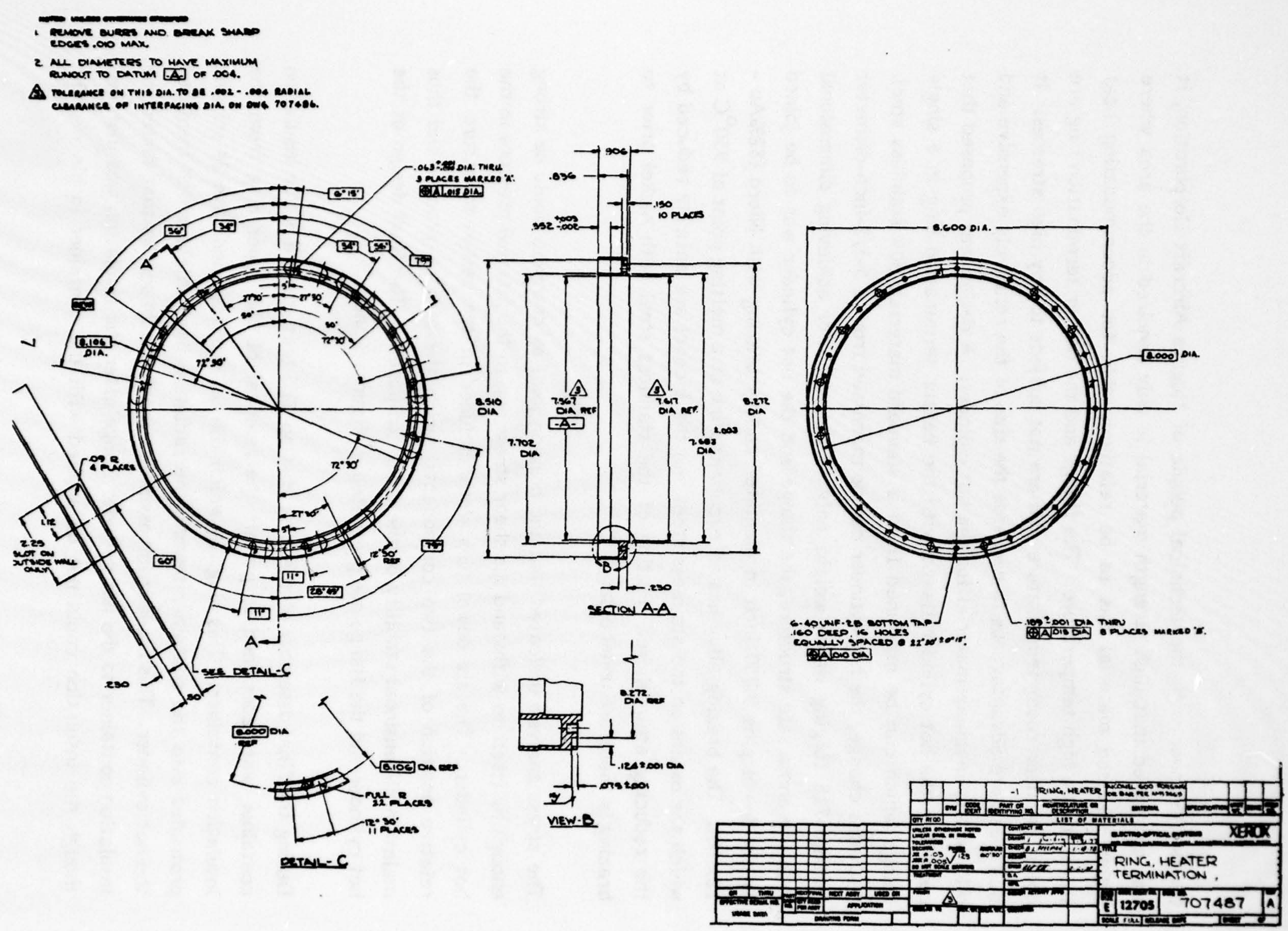


Figure 2. Ring, Heater Termination

the hot cylinder with the technical people of Hughes Aircraft Corporation, it was confirmed that high strength material is only required in the area where highly stressed material has to be relatively thin for accommodating heat transfer at a high temperature. The flange and the heater termination ring are operating near room temperature and are not subject to any high stresses. It was therefore advantageous to decrease the size of the relatively expensive and difficult-to-machine material for the hot cylinder. A design was proposed that combined the hot cylinder flange with the heater termination ring in a single flange which can be machined from a standard material, 304 stainless steel. With this change, the hot cylinder can be machined from a 5-1/2-inch-diameter Inconel 718 forging which weighs only 48 pounds. For achieving dimensional stability and a safe structure, the flange and the hot cylinder was to be joined by six dowel pins 0.250 inch in diameter and by brazing with Nioro (82%Au - 18%Ni). The brazing alloy has an excellent flow at a melting point of 950^{o}C at which the oxides on the stainless steel and the Inconel are entirely reduced by the reducing atmosphere. Plating of the stainless steel with nickel prior to brazing is therefore unnecessary.

The stress analysis indicated that the brazing joint as designed would be strong enough by itself to withstand the shear stress due to the internal pressure in the hot cylinder. The six dowel pins were included in the design to ensure the relative position of the two components during the brazing process and thus maintain dimensional stability of the final component. The final design of the hot cylinder and the flange are presented in Figures 3 and 4.

During the final assembly of the first Hi-Cap TES unit, the lid of the insulation container was redesigned to permit the removal of the upper ring from the insulation container. This ring, to which the lid was fastened with 24 screws, protruded into the container beyond the radiation heat shield which insulated the hot cylinder. This made it impossible to reach the 24 screws that fasten the insulation container to the hot cylinder flange after the insulation was installed though the insulation could not be applied with the container in place. The

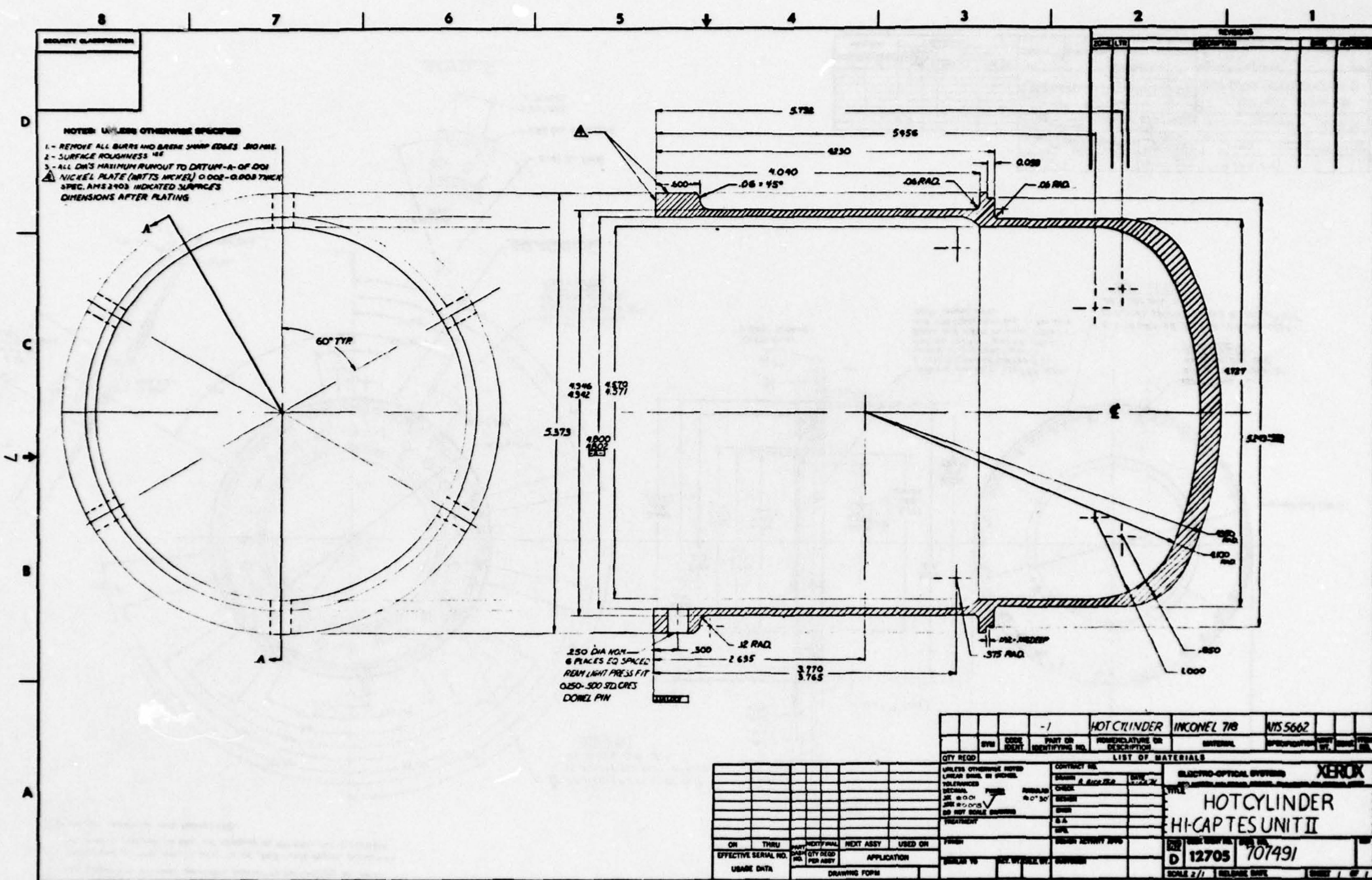


Figure 3. Hot Cylinder - Hi-Cap TES Unit II

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

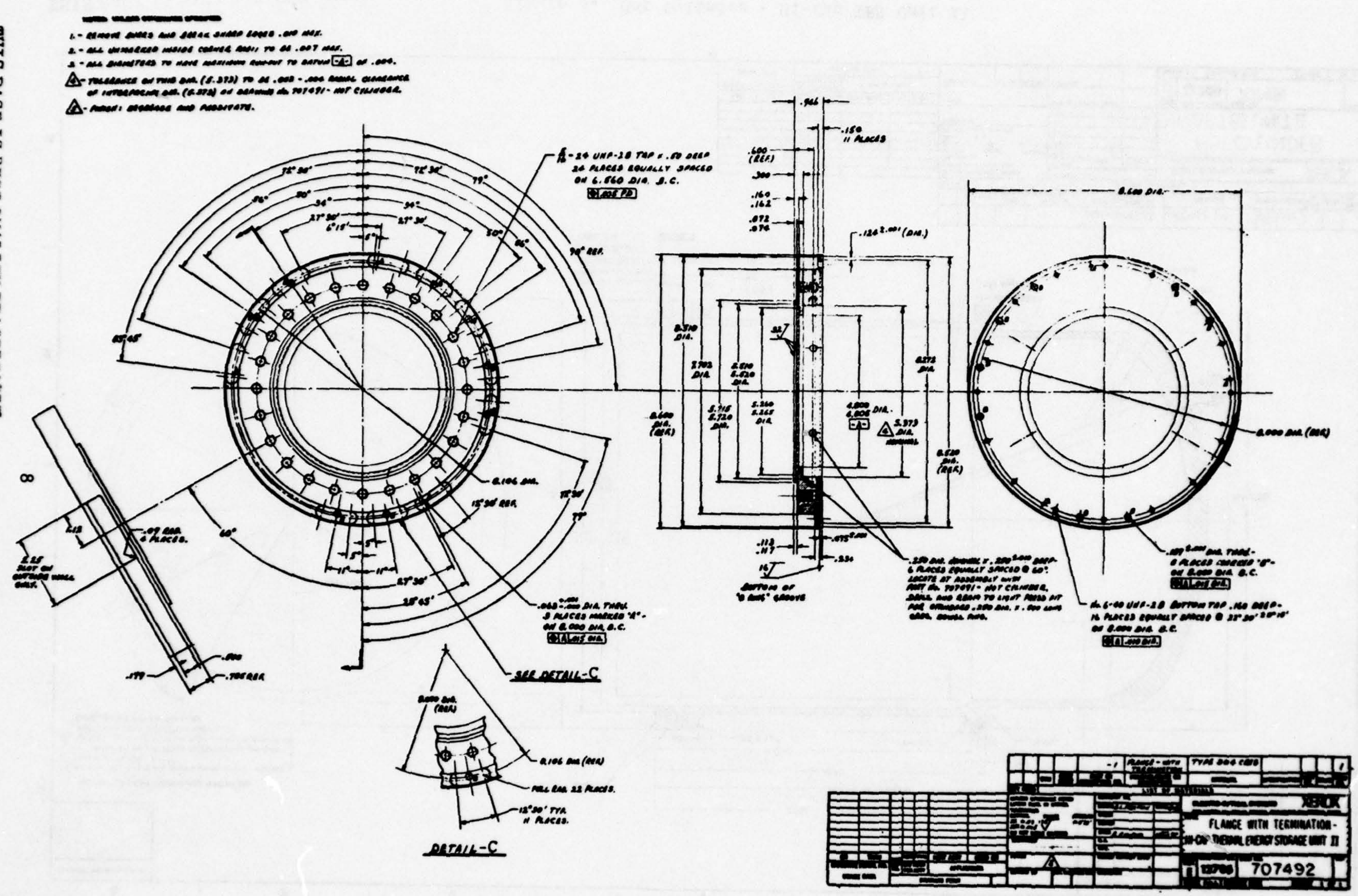


Figure 4. Flange with Termination - Hi-Cap Thermal Energy Storage Unit II

initial modification as shown in Figures 5 and 6 aimed at saving the already machined insulation container. The O-ring groove was therefore machined into the new lid. In this configuration, the O-ring had to slide over the bolt holes in the container which had to be covered by shims during the closing of the container to prevent shedding of the O-ring. The container design has been revised to eliminate this difficulty with the O-ring by designing the O-ring groove into the container as shown in Figures 7 and 8.

2.3 INSULATION

After establishing the thermal losses for the first Hi-Cap TES unit, it appeared that conduction occurs along the radiation heat shield into the flange of the hot cylinder. An analysis indicated that this could be avoided by placing a conduction barrier consisting of Flexible Min-K insulation between the radiation heat shield and the flange. The insulation design of the second Hi-Cap TES unit is shown in Figure 9, which varies solely from the insulation of the first Hi-Cap TES unit by the 1-inch thick ring of Flexible Min-K material that separates the radiation shield from the flange.

2.4 THERMAL ENERGY STORAGE UNIT

No changes were made in the design of the thermal energy storage unit itself. If more data on the behavior of the thermal energy storage material would have become available, a decrease in the volume of the thermal energy storage material container would have been undertaken. In the present design the thermal energy storage volume is oversized by 5 percent to ensure free expansion of the melting material and thus prevent possible rupture of the container. The larger volume, however, is detrimental to the heat transfer and causes the temperature range over which the stored latent heat is extracted to be larger than necessary.

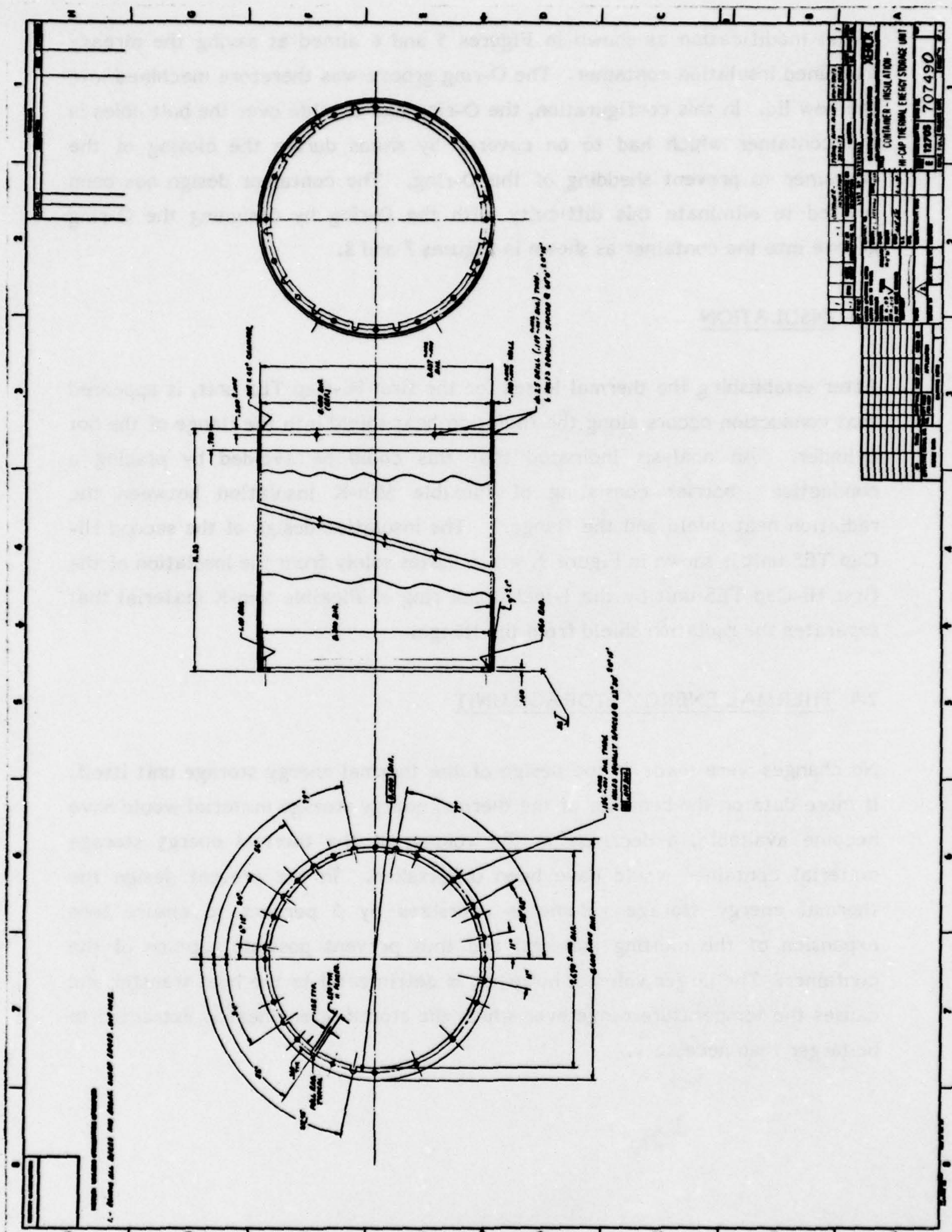


Figure 5. Container - Insulation - Hi-Cap Thermal Energy Storage Unit

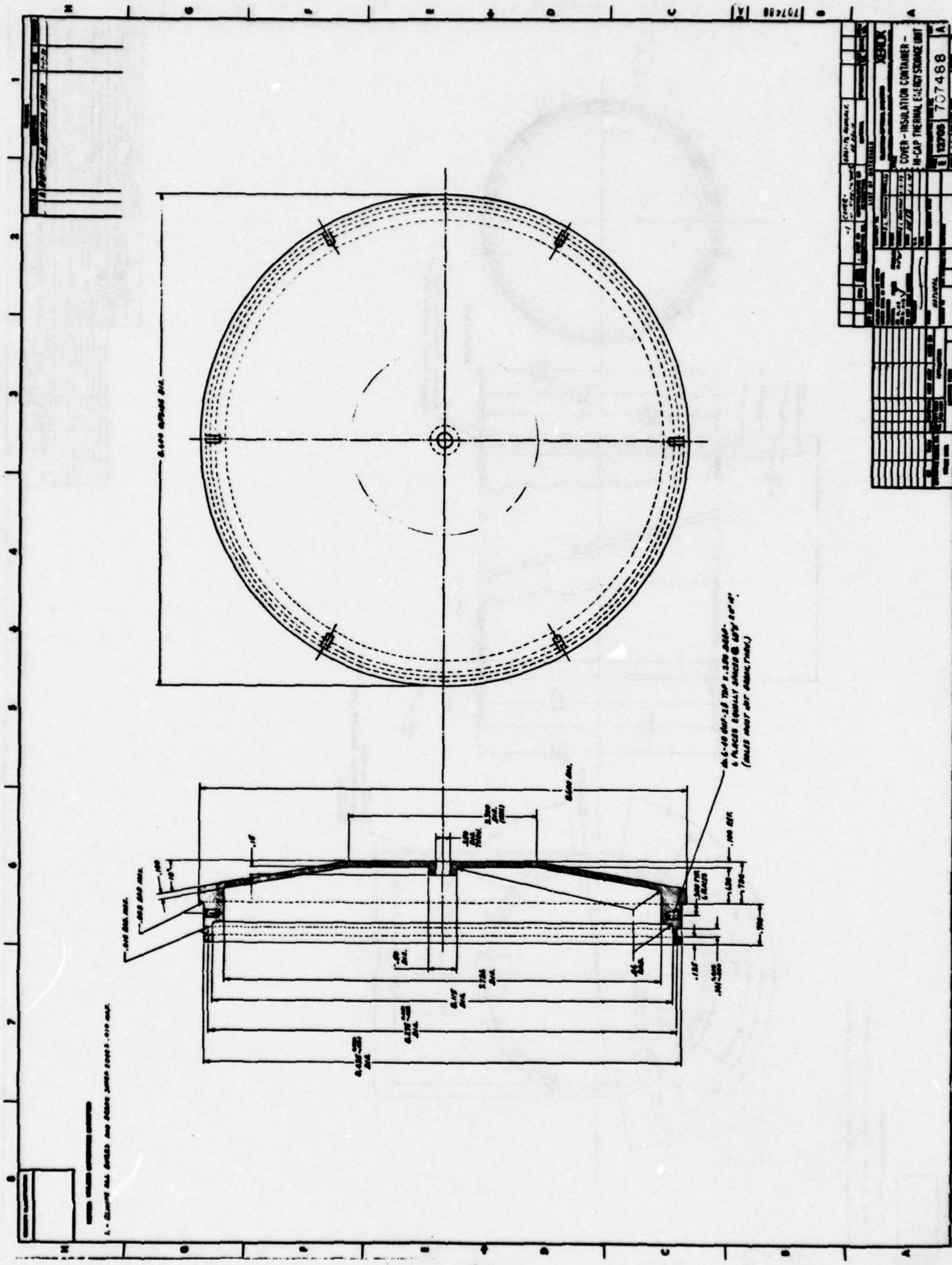


Figure 6. Cover - Insulation Container - Hi-Cap Thermal Energy Storage Unit

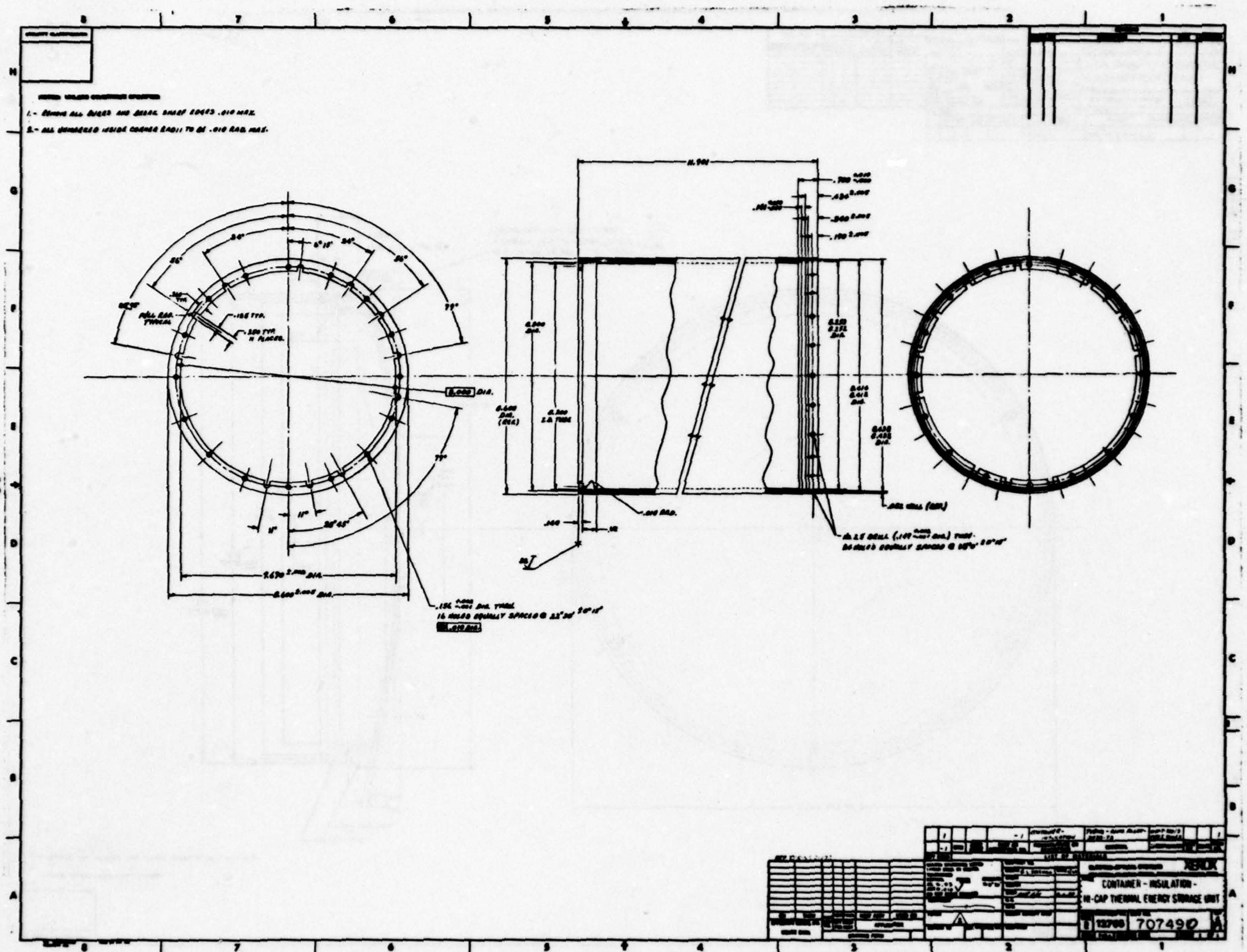


Figure 7. Container - Insulation - Hi-Cap Thermal Energy Storage Unit

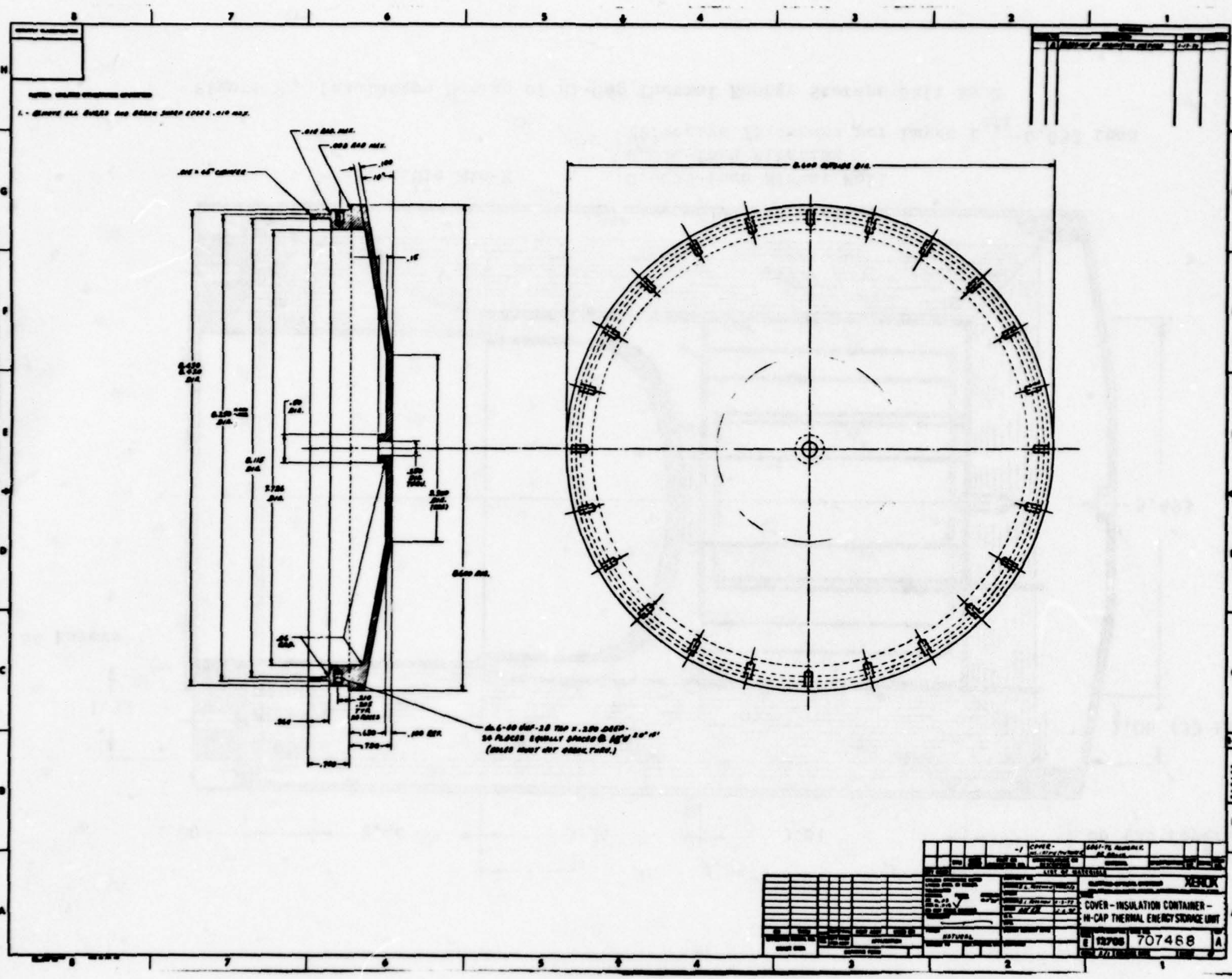


Figure 8. Cover - Insulation Container - Hi-Cap Thermal Energy Storage Unit

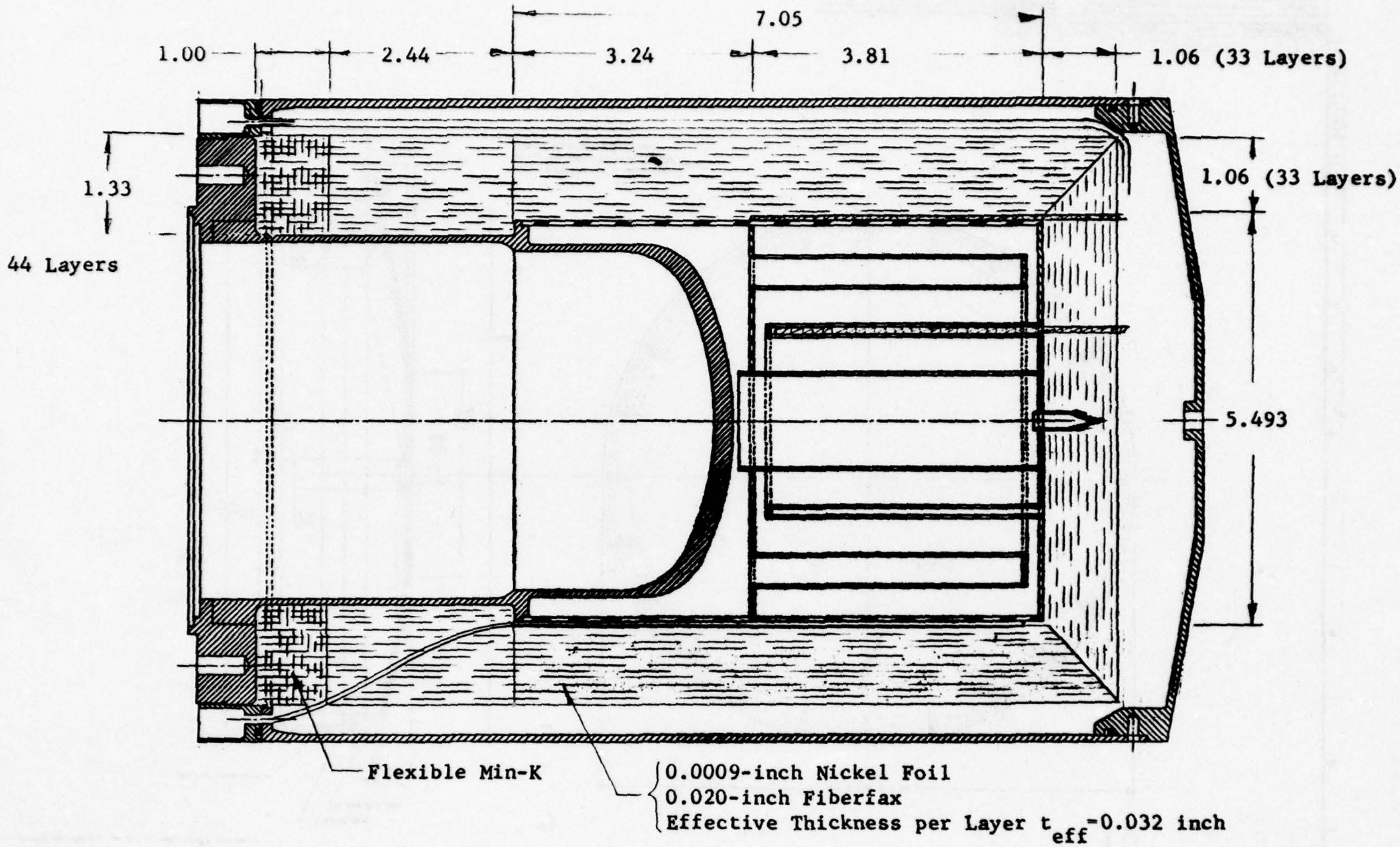


Figure 9 Insulation Design of Hi-Cap Thermal Energy Storage Unit No.2

For completeness the components of the thermal energy storage unit are shown in Figures 10, 11, and 12, and the assembly drawing in Figure 13.

2.5 INSTRUMENTATION

The first Hi-Cap thermal energy storage unit was intended to be primarily instrumented with RTDs for measuring two temperatures of the TES unit. One of the signals was to be used for temperature control. After testing several RTDs over the temperature range of the TES unit, it became apparent that the operating temperature of the TES unit was exceeding the allowable temperature of the RTDs. This had been pointed out in the literature and by the manufacturers of these devices. Only one of the RTDs that were bought from the manufacturer fully assembled had survived several thermal cycles. It was installed in the first Hi-Cap TES unit with one 1/8-inch diameter and one 1/16-inch diameter Inconel sheathed K calibration thermocouple. The single RTD, however, failed after the first thermal cycle of the TES unit, while the thermocouples indicated temperatures without problem over the entire operating range.

The experience with the instrumentation of the first Hi-Cap TES unit indicated that 1/16-inch-diameter Inconel sheathed K calibration thermocouples would constitute the most appropriate instrumentation. The three thermocouples would be mounted at three axially different locations. Future tests and systems considerations would later determine which of the three thermocouples would be used for the temperature control of the unit and which temperature reading would give the best indication of the charged/discharged condition of the TES unit.

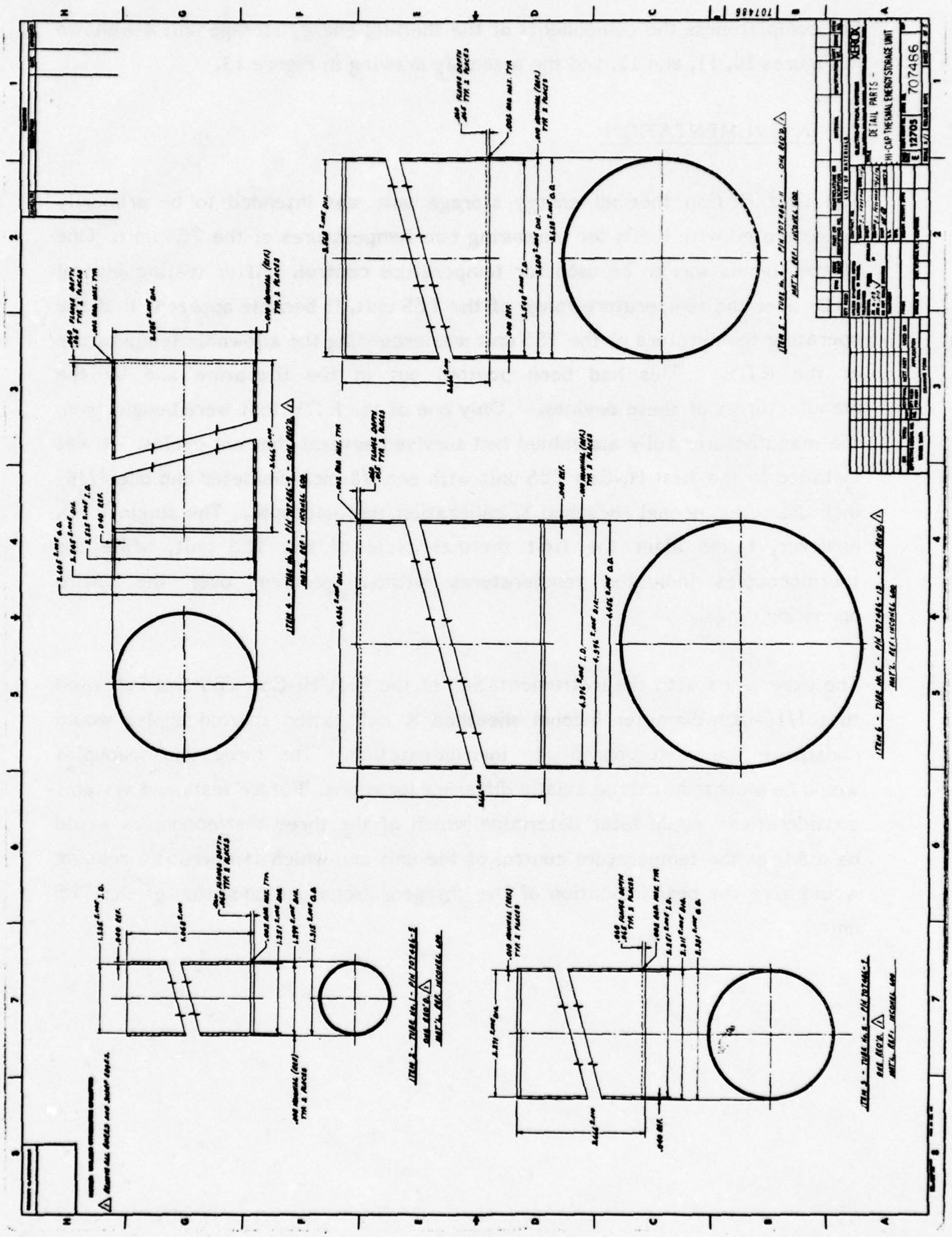


Figure 10. Detail Parts - Hi-Cap Thermal Energy Storage Unit

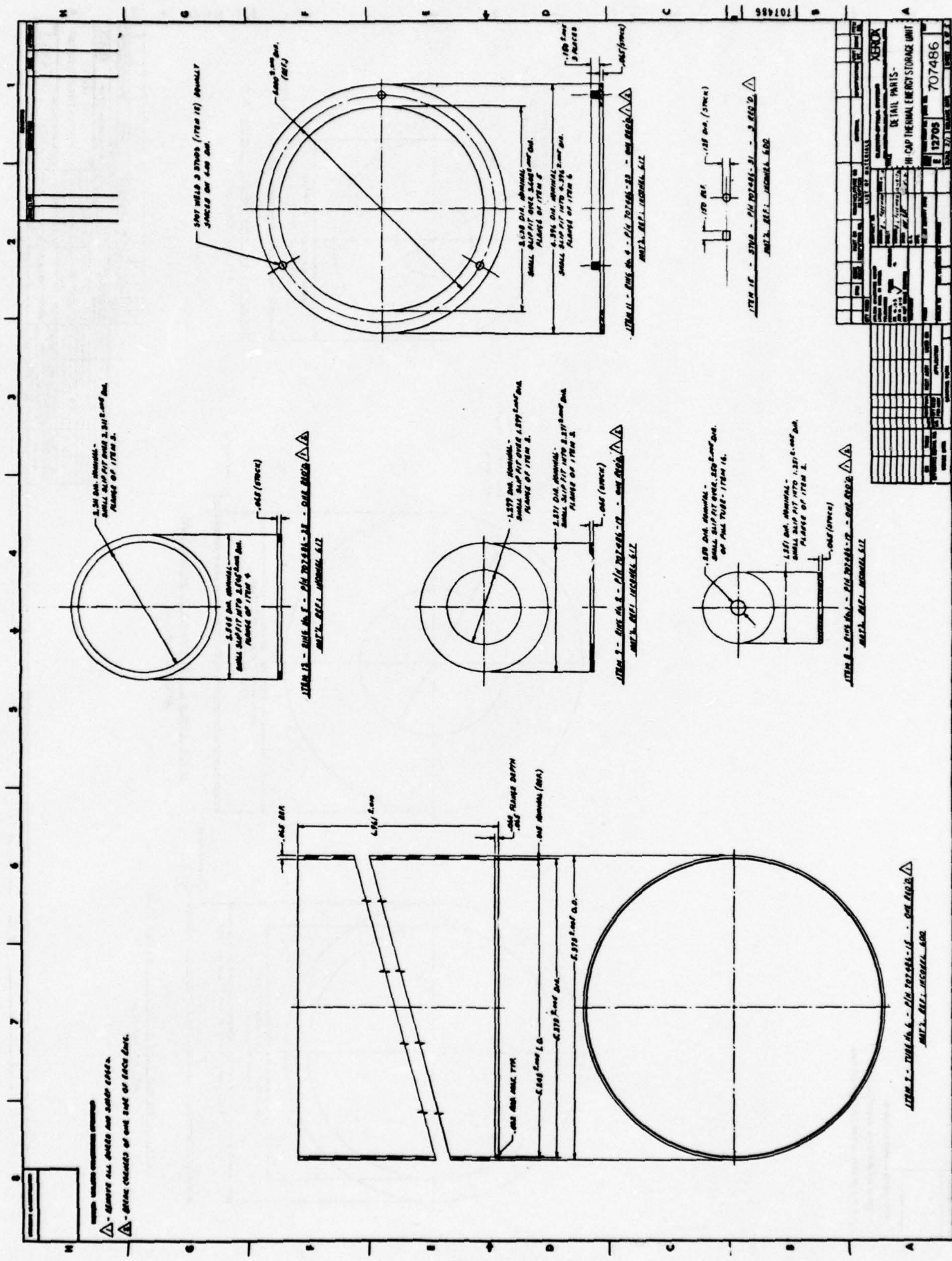


Figure 11. Detail Parts - Hi-Cap Thermal Energy Storage Unit

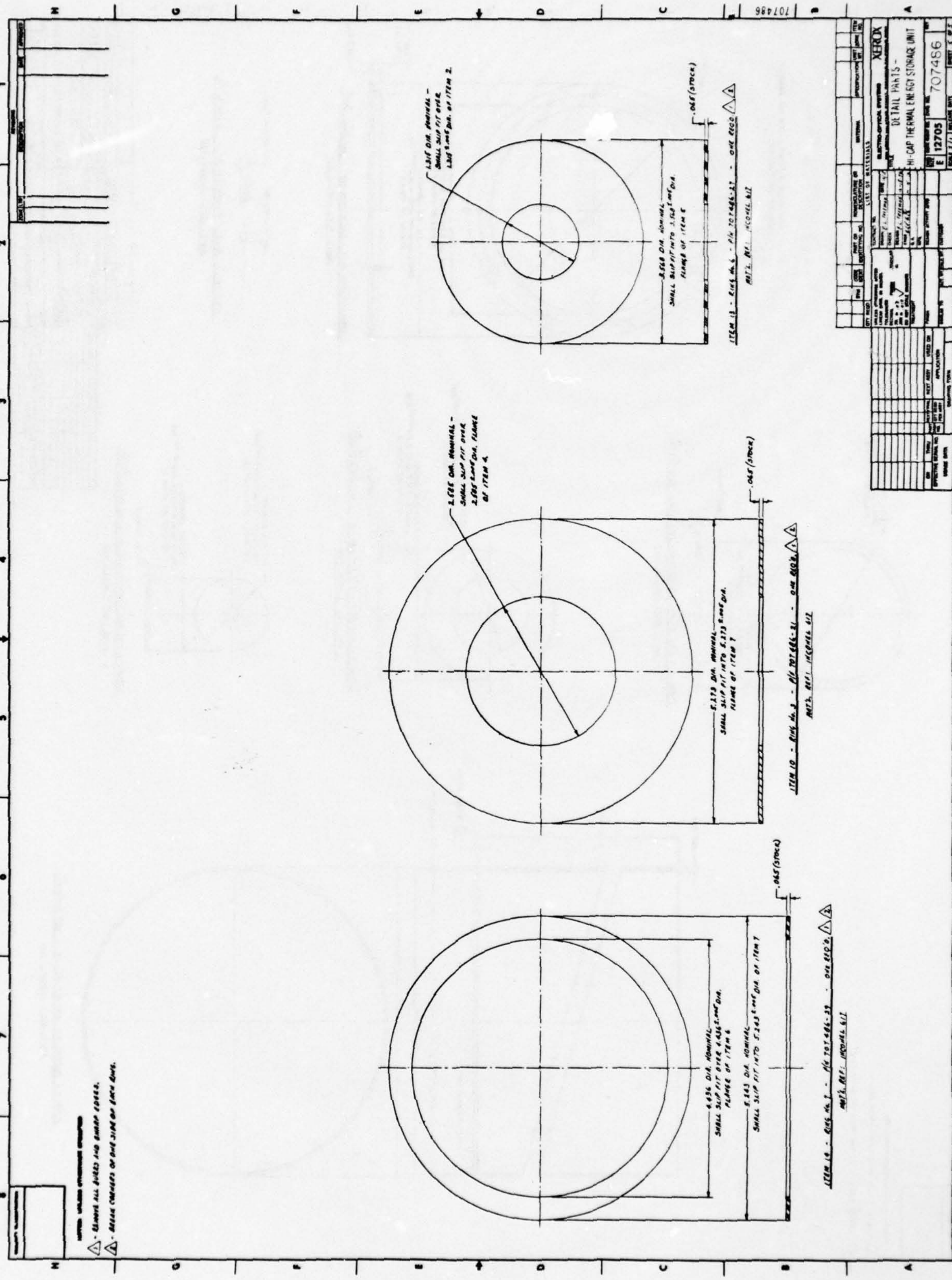
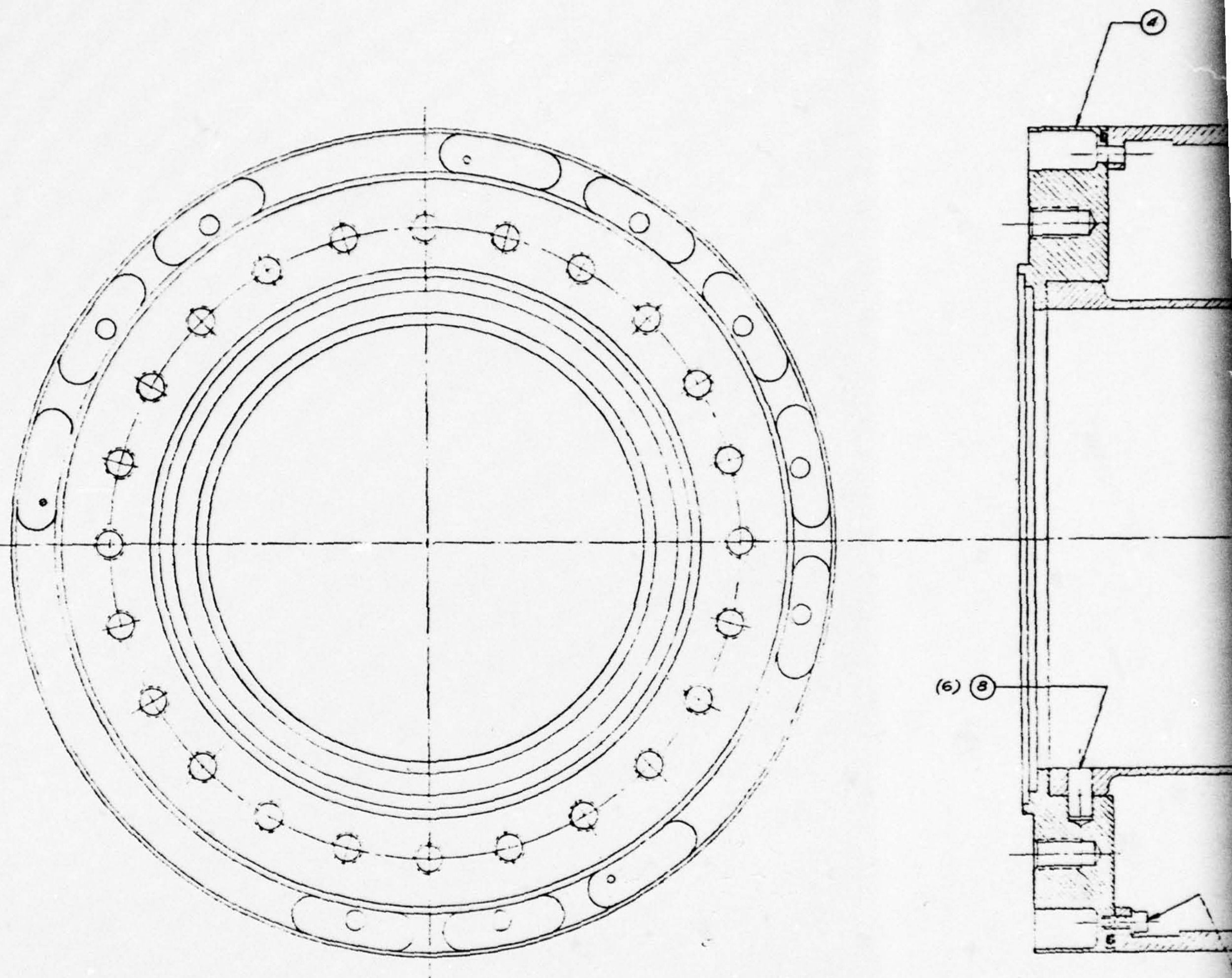


Figure 12. Detail Parts - Hi-Cap Thermal Energy Storage Unit

SECURITY CLASSIFICATION

NOTES: UNLESS OTHERWISE SPECIFIED



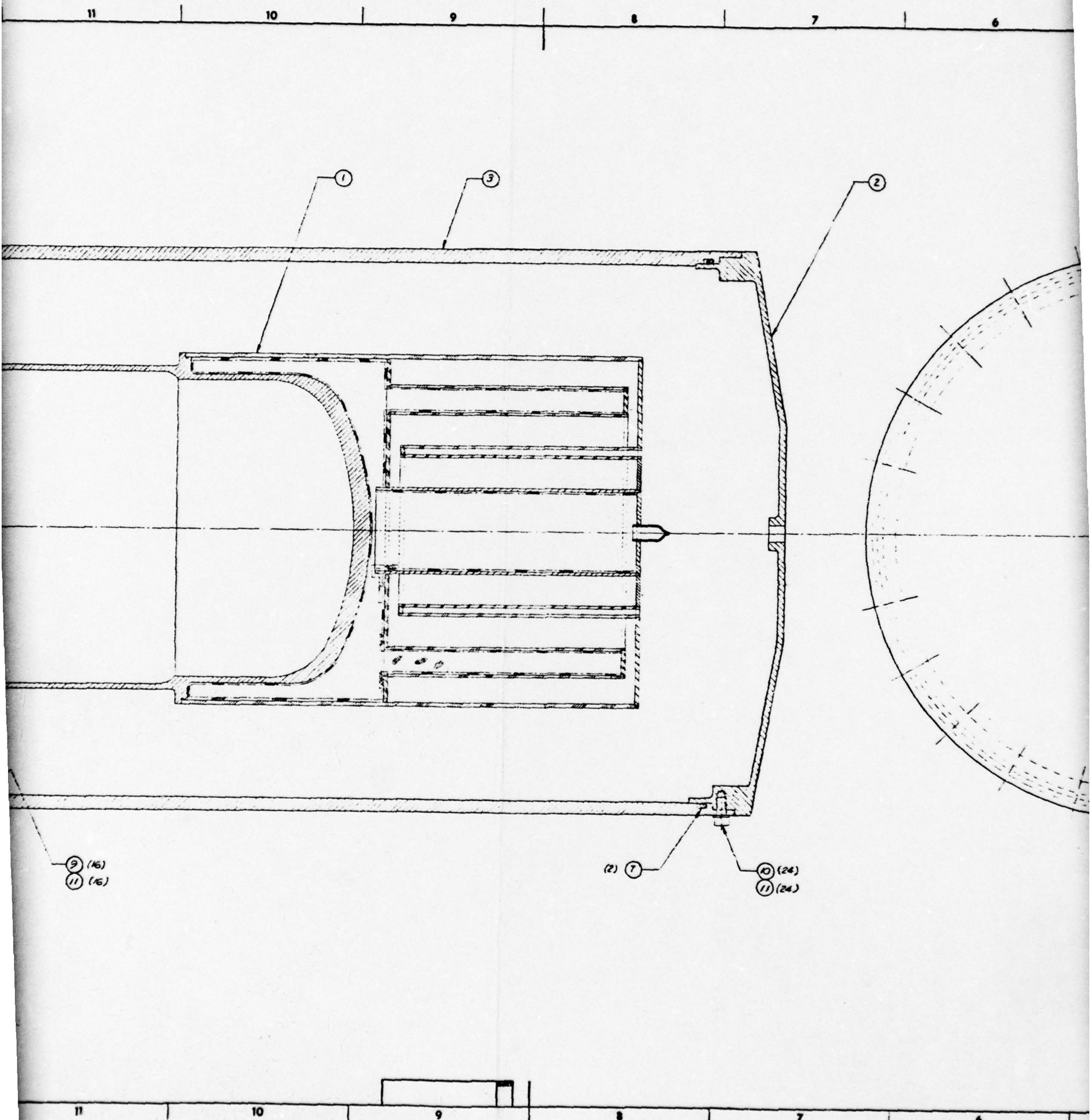
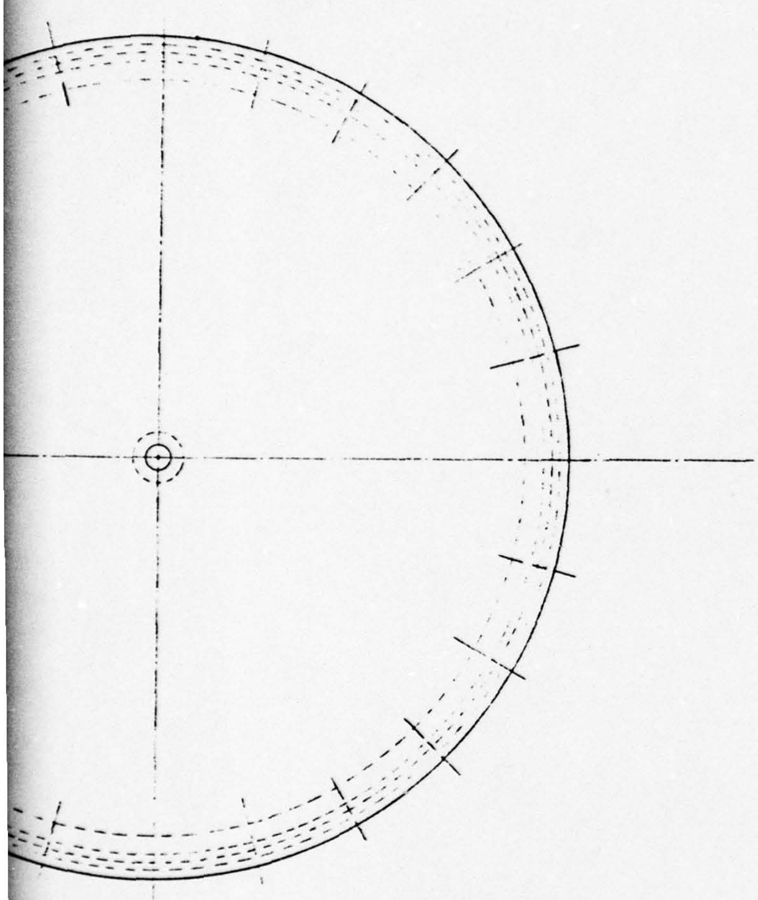


Figure 13. Assembly - Hi-Cap Thermal Energy Storage Unit No. 2



THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

QTY REQD -1	SYM	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	UNIT WT.	ZONE	ITEM NO.
40				WASHER-LOCK #6 CRES					
24				SCREW-SOC HD #6-40UNF x .5 LG CRES					10
16				SCREW-SOC HD #6-40UNF x .25 LG CRES					9
6				DOWEL PIN CRES .250 DIA x .50 LG					8
2			2-172	"O" RING					7
									6
									5
1			707492-1	FLANGE					4
1			707490-1	CONTAINER					3
1			707488-1	COVER					2
1			707486-1	ASSY					1

LIST OF MATERIALS

UNLESS OTHERWISE NOTED LINEAR DIMS IN INCHES TOLERANCES DECIMAL .XX ± .03 .XXX ± .010 FINISH ANGULAR DO NOT SCALE	CONTRACT NO. DRAWN DATE CHECK DESIGN E. A. HEEMAN	ELECTRO-OPTICAL SYSTEMS, INC. A XEROX COMPANY
MATERIAL	MFG.	TITLE ASSEMBLY - HI-CAP THERMAL ENERGY STORAGE UNIT
TREATMENT FINISH	DESIGN ACTIVITY APPD	SIZE J · CODE IDENT NO. 12705 · DWG NO. 707489
SIMILAR TO · ACT. WT. · CALC. WT.	CUSTOMER	SCALE · RELEASE DATE · SHEET OF

ON	THRU	MATERIAL QTY REQD PER ASSY	NEXT ASSY	USED ON
EFFECTIVE SERIAL NO.			APPLICATION	
USAGE DATA		DRAWING LEVEL		

707489

3

SECTION III

FABRICATION

3.1 HOT CYLINDER AND FLANGE WITH TERMINATION RING

The hot cylinder was machined from a 5-1/2-inch-diameter Inconel 718 forging which had a weight of 48 pounds. The flange with the termination ring was machined from a stainless steel 304 plate. The two components were joined first with six 1/4-inch dowel pins and then brazed together with NIORO (82%Au18%Ni). The finished hot cylinder is shown in Figures 14 and 15.

3.2 CASTING OF THERMAL ENERGY STORAGE MATERIAL

A change in the casting process of the thermal energy storage material was initiated with the manufacturing of this second Hi-Cap TES unit. During the fabrication of the Thermal Energy Storage Demonstration Unit and the first Hi-Cap TES unit, the three fluoride salts, LiF, MgF_2 and KF, of which the eutectic is composed, were combined in the eutectic proportion and mixed as good as possible. The mixture was then poured into the casting fixture. The powder occupied a total volume which was more than three times the volume of the final cast. Because absolute uniformity of the initial salt powder could not be achieved during mixing, often the material would not drop into the casting form at the lower part of the casting fixture. After the first melt, the material would be non-uniform and not of the eutectic consistency and the casting incomplete. The cast had to be remelted for a second and often for a third time. Though there was a chance of accomplishing the casting of the TES material in a single melting process in the retort, in actual experience the material had to be melted three times to achieve a complete cast of uniform material.

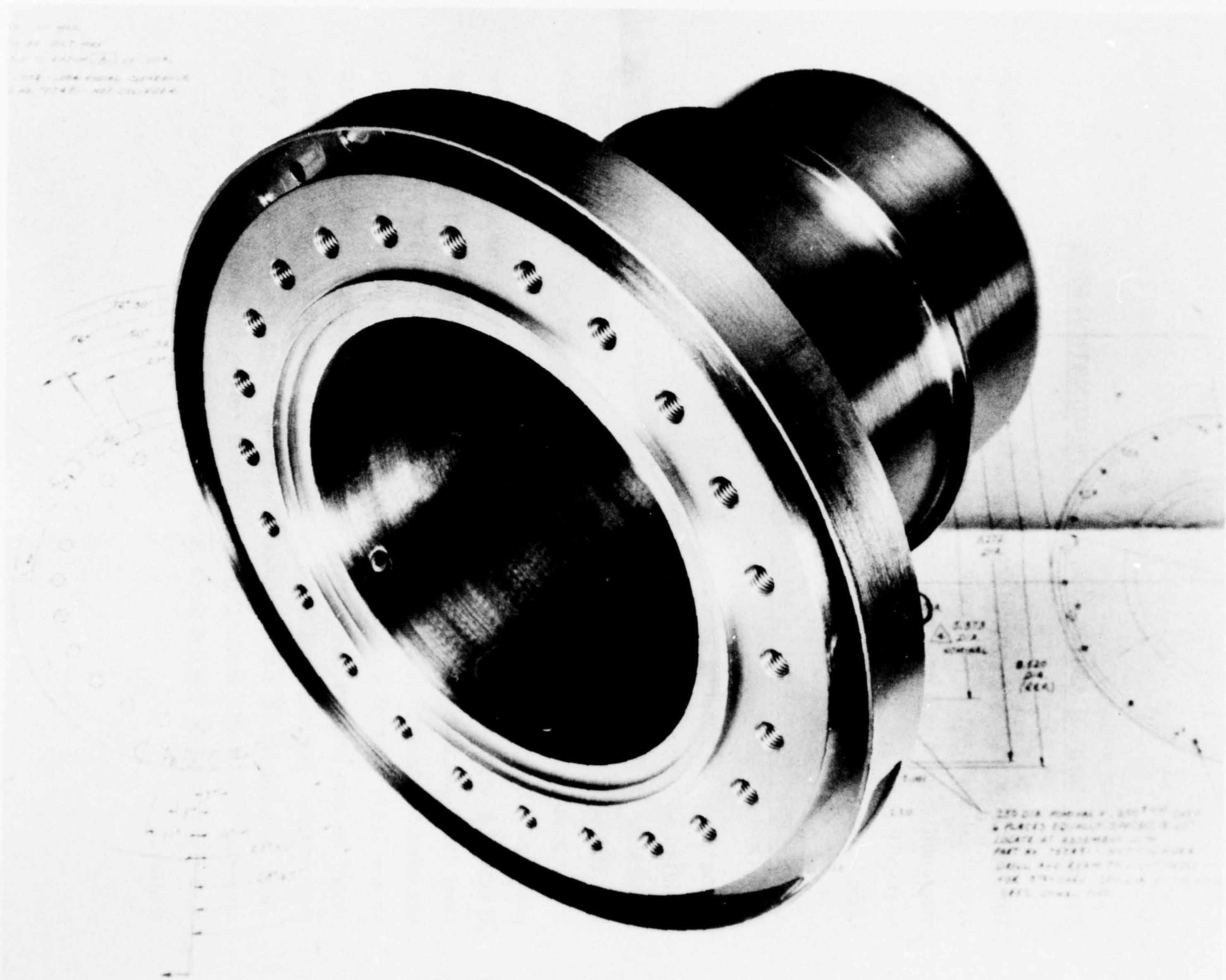


Figure 14. Hot Cylinder of Hi-Cap Thermal Energy Storage Unit No. 2 (Bottom View)

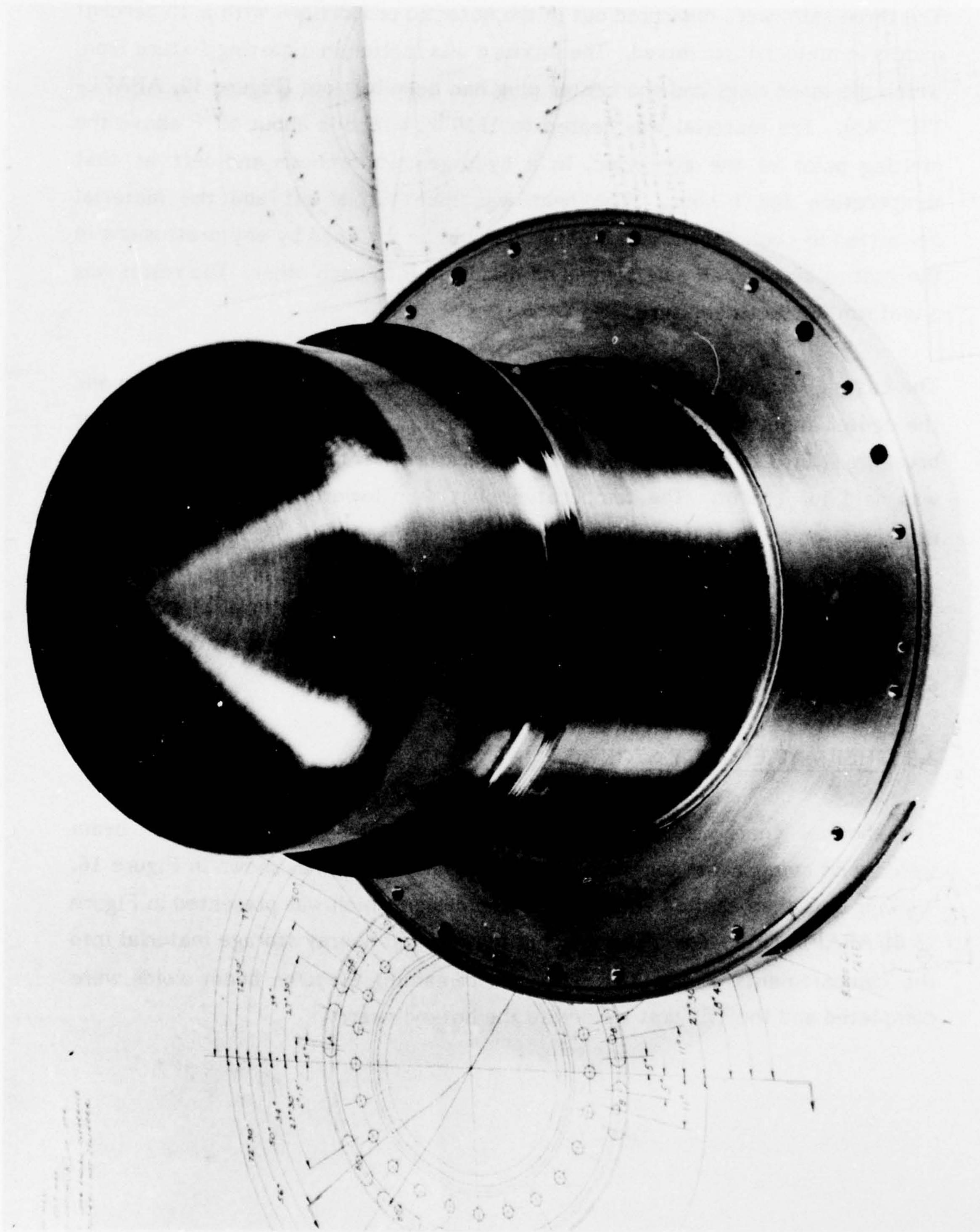


Figure 15. Hot Cylinder of Hi-Cap Thermal Energy Storage Unit No. 2 (Top View)

Based on that experience the process of casting the TES material was modified. The three salts were measured out in the eutectic proportions with a 10 percent excess in material and mixed. The mixture was molten in a casting fixture from which the inner rings and the center plug had been left out (Figure 30, AFAPL-TR77-65). The material was heated to 1350°F, which is about 40°F above the melting point of the euctectic, in a hydrogen atmosphere and left at that temperature for 1 hour. The heat was then turned off and the material permitted to cool. Because no material could be retained by any protrusions in the casting fixture, all salt compound dissolved into each other. The result was a uniform euctectic mixture.

The casting fixture was then assembled with the center plug, the inner tube and the center tube. The TES material was placed into the casting fixture after breaking it into smaller pieces. The temperature was raised to 1370°F where it was held for 1 hour. The temperature was then lowered to 1310°F where it remained for one half hour prior to turning off the heat.

The resulting cast was nearly without voids. The TES material pieces fitted without difficulty into the thermal energy storage unit which made the final assembly of the TES unit very easy.

3.3 THERMAL ENERGY STORAGE UNIT

The thermal energy storage unit was assembled by initially electron beam welding its components together into three subassemblies as shown in Figure 16. Wicking was then applied according to the design which was presented in Figure 28 of AFAPL-TR-77-65. After placing the thermal energy storage material into the compartments of the TES unit, the remaining electron beam welds were completed and the TES unit welded to the hot cylinder.

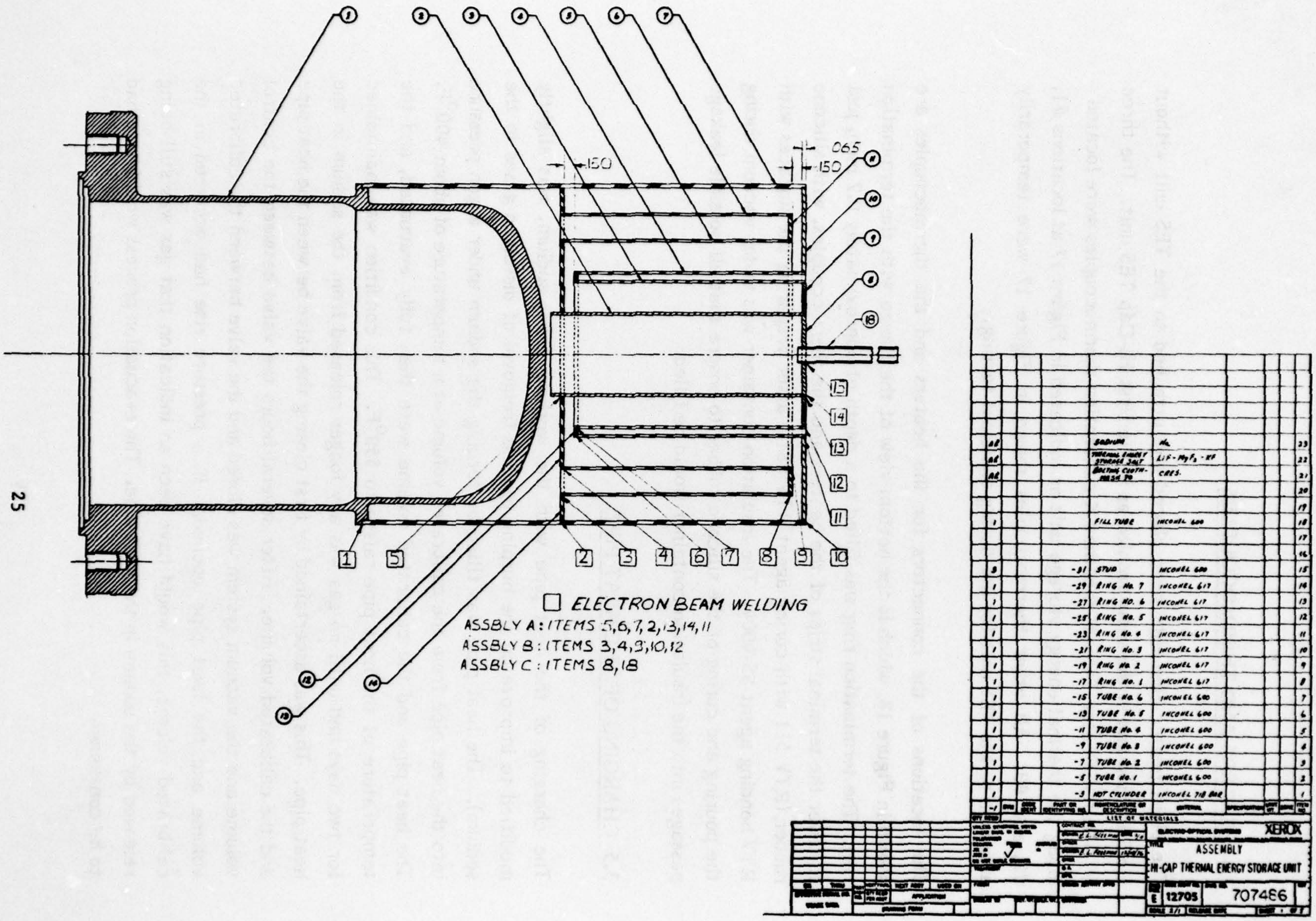


Figure 16. Welding Schedule for Hi-Cap Thermal Energy Storage Unit

3.4 HEATERS AND THERMOCOUPLES

The eight heater elements were placed and attached to the TES unit without modification and in the same fashion as in the first Hi-Cap TES unit. The three 1/16-inch diameter Inconel sheathed K calibration thermocouples were located along the thermal energy storage unit as indicated in Figure 17 at locations #1, #2, and #3. All other thermocouples shown in Figure 17 were temporarily attached to the TES unit for use during checkout testing.

The locations of the connectors for the heaters and the thermocouples are shown in Figure 18, which is the bottom view of the flange with the termination ring. The termination ring was filled to a depth of approximately 0.2 inch, just to cover the terminal strips of the heaters and the thermocouples, with silicone rubber (RTV 511 with curing agent RTV 9811) after preparing the surfaces with RTV bonding agent SS-4004. The insulation container was under vacuum during the pouring and curing of the silicone rubber to ensure that all possible leakage passages into the insulation container would be filled.

3.5 CHARGING OF THE HEAT PIPE

The charging of the heat pipe with the working fluid, sodium, was slightly modified to improve on the burping process (removal of dissolved gases in the sodium). The heat pipe was filled by forcing the sodium under argon pressure into the heat pipe from the calibrated volume at a temperature of about $400^{\circ}F$. The heat pipe and the calibrated volume were then fully evacuated, and the temperature of the heat pipe raised to $550^{\circ}F$. This condition was maintained for two days and until no gas was any longer released from the sodium in the heat pipe. This was ascertained by first closing the valve between the heat pipe and the calibrated volume. After several hours the valve between the control volume and the vacuum system was closed and the valve between the calibrated volume and the heat pipe opened. If a pressure rise had occurred in the calibrated volume, this would have been an indication that gas was still being released by the sodium in the heat pipe. The evacuation process would have had to be continued.

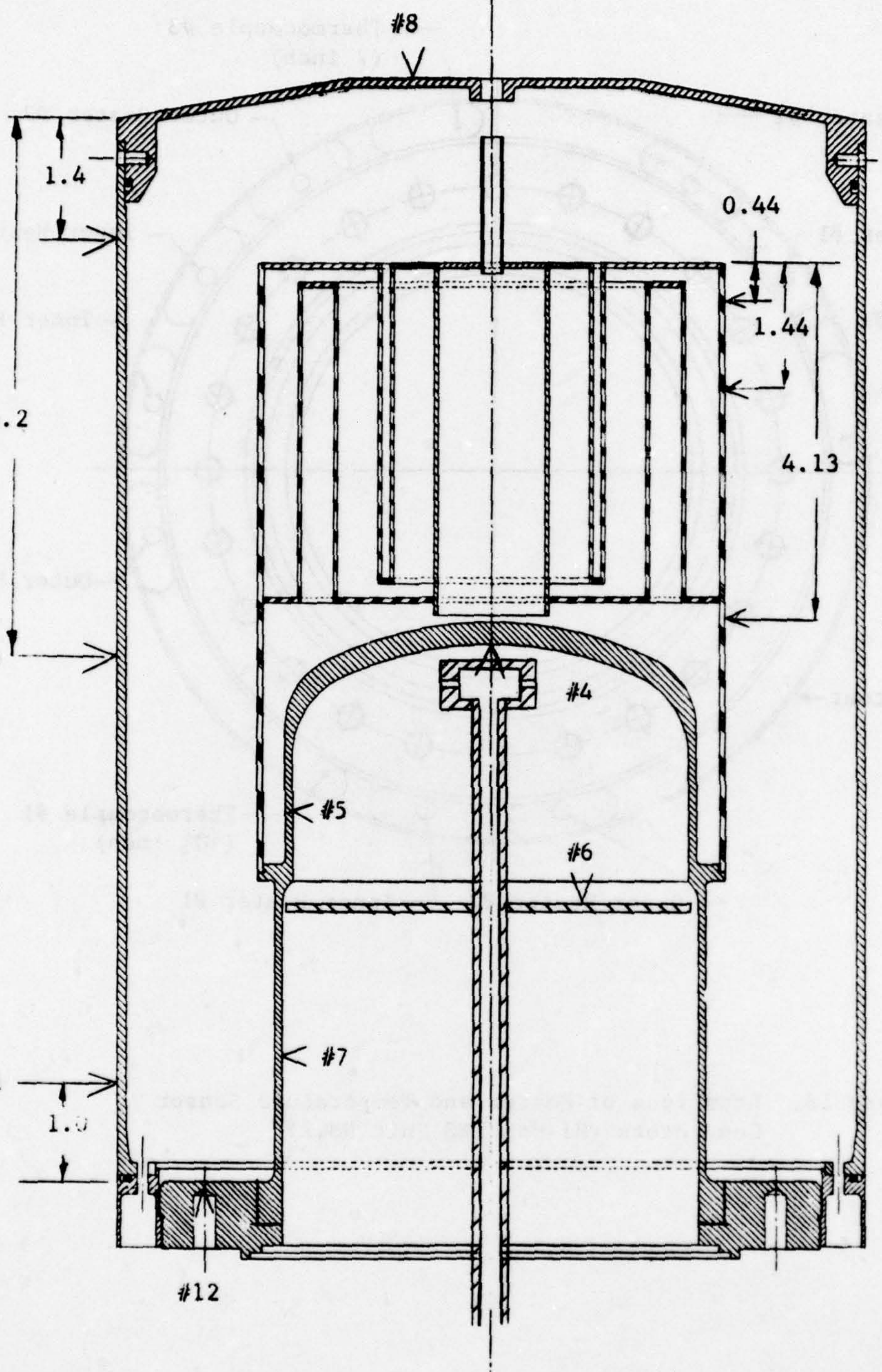


Figure 17. Locations of Permanent and Temporary Thermocouples During Performance Testing

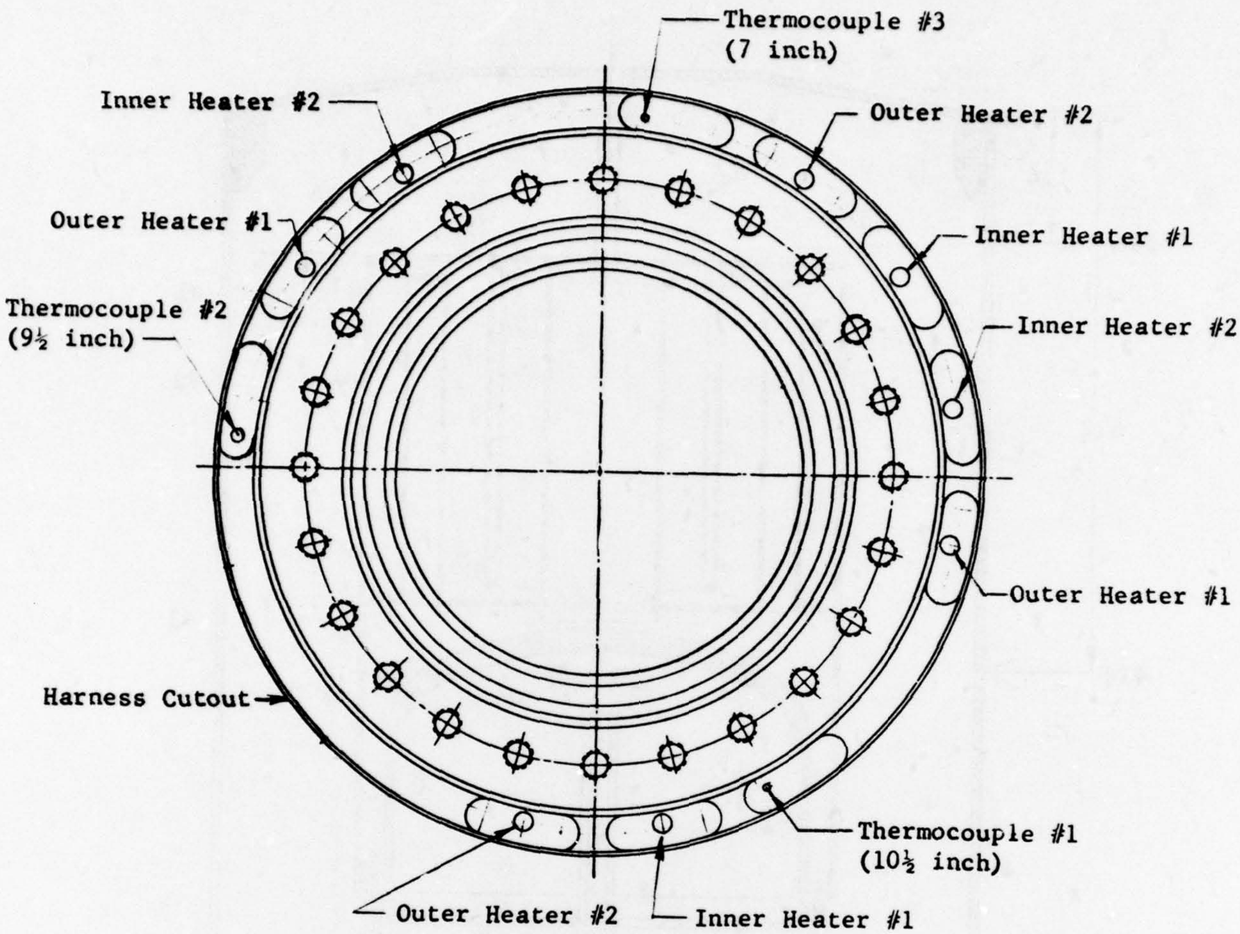


Figure 18. Locations of Heater and Temperature Sensor Connectors (Hi-Cap TES Unit No.2)

After the initial gas removal had been completed, the temperature of the heat pipe was raised to the operating temperature with the valve between the heat pipe and the calibrated volume closed. Upon reaching the operating temperature, the valve between the vacuum system and the calibrated volume was closed. The valve between the heat pipe and the volume was opened for a very short time until a rapid temperature rise was indicated by the thermocouple located at the tube connecting the heat pipe and the volume. This increase in temperature was due to the flow of sodium vapor which condenses and gives off latent heat. Since a small pressure rise to 0.2 mm Hg occurred in the volume, indicating that some non-condensable gas had been transferred from the heat pipe, this burping process was repeated. But with each opening of the heat pipe to the volume, some sodium was transferred as indicated by the heating of the volume. If the gas pressure in the volume had not decreased after successive burping, the sodium, which has been tansferred into the volume would have had to be pushed back into the heat pipe under pressure after the heat pipe has cooled down to 550°F. The entire evacuation process would have had to be repeated.

At the end of the burping, the volume was removed and weighed to ensure that no more than an allowable surplus of sodium had been transferred back from the heat pipe. The total amount of sodium that remained in the heat pipe was 101 grams (100 grams was the design value).

SECTION IV

TESTING OF HIGH CAPACITY VUILLEUMIER CRYOGENIC COOLER THERMAL ENERGY STORAGE UNIT NO. 2

4.1 TEST CONSIDERATIONS

The primary objective of the testing of the second thermal energy storage unit was the determination of the thermal losses, the confirmation of the thermal capacity, and ascertaining the correct functioning of the heat pipe. The overall design characteristic for the Hi-Cap TES unit had already been established during the testing of the first Hi-Cap TES unit which was described in AFAPLTR-77-65.

4.2 TEST SETUP

The setup for testing the second Hi-Cap TES unit was the same as for the first unit, though the number of thermocouples and their locations, as shown in Figure 17, was slightly different.

4.3 PERFORMANCE TESTING

4.3.1 THERMAL LOSSES

The thermal losses from the TES unit were determined by the power input to the unit during steady state. The test results are shown in Figure 19. When the thermal losses of the two Hi-Cap TES units are compared, the second TES unit is found to loose about 8W less at the nominal operating temperature of 1250°F than the first unit. This seems to indicate that the conduction barrier between the radiation heat shield and the end flange has produced the desired decrease in the heat loss.

4.3.2 THERMAL CAPACITY

The thermal capacity of the second Hi-Cap TES unit was established by charging and discharging the unit while recording the temperatures and reducing the data. The temperatures, indicated by thermocouple #3, during charging with an input power of P_{in} = 437W and discharging by thermal losses are presented in Figures 20 and 21, respectively. The sensible and total latent heat released during the discharge is plotted in Figure 22 as a function of the operating temperature. From Figure 23 it is seen that the latent heat for which the Hi-Cap TES unit has been designed is released over a range of $\Delta T = 37^{o}F$. The apparent thermal capacity as a function of temperature is shown in Figure 23. The results closely agree with those which were presented in Figures 43 through 46 of report AFAPLTR-77-65 for the first Hi-Cap TES unit. The behavior of the second Hi-Cap TES unit under high discharge rates is presented in Figures 24 through 27. These data can be compared with those of Figures 57 through 60 of report AFAPLTR-77-65. The temperatures shown in Figure 25 are almost identical with those measured with the first Hi-Cap TES unit, though the discharge time at which thermocouple #3 drops from $1305^{o}F$ to $1295^{o}F$ is shorter. The reason for this difference lies in the incomplete charging of the TES unit prior to the start of the discharge cycle.

The TES unit was charged with a total power input of P_{in} = 554.5 watts. The effective charging rate at the end of the charging cycle is

$$P_{TES} = P_{in} - P_L$$

where:

P_{TES} = power into the TES unit
P_{in} = total electrical power to the TES unit
P_L = power loss to the environment

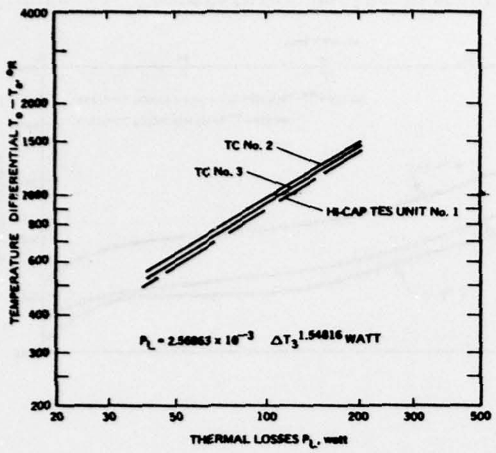


Figure 19. Thermal Losses (TES Unit No.2 Final Configuration)

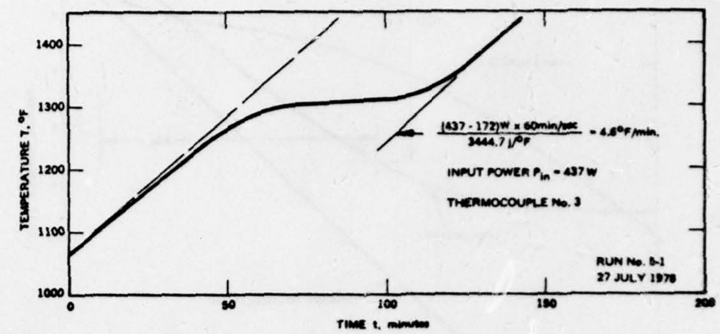


Figure 20. Temperature During Charging

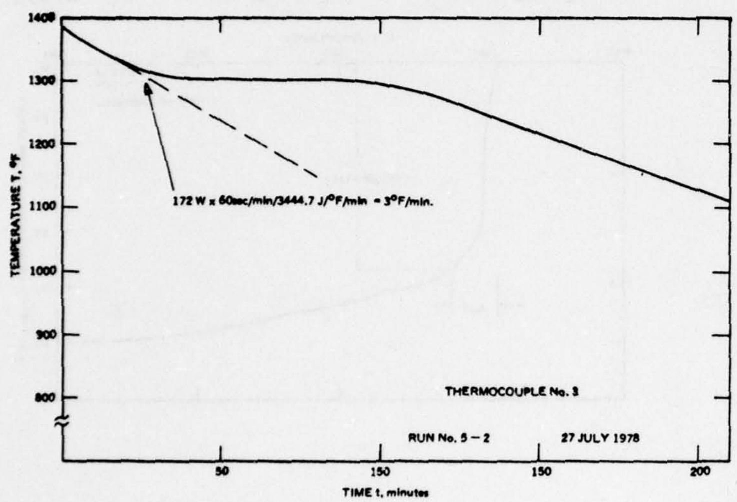


Figure 21. Temperature During Discharge

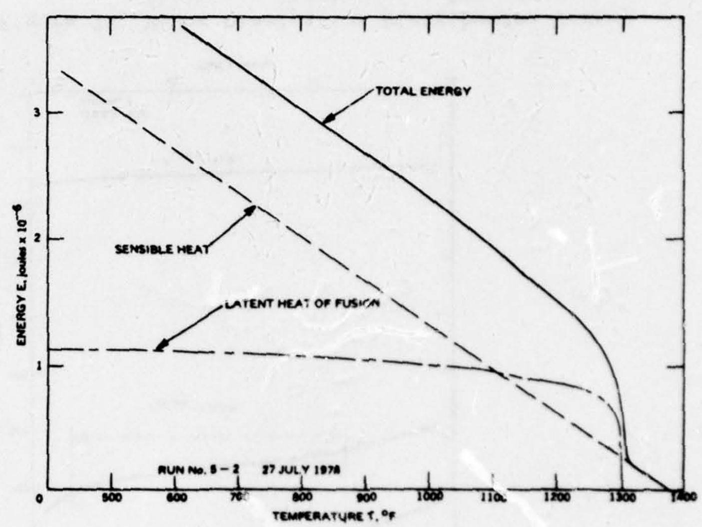


Figure 22. Extracted Energy (Discharge By Thermal Losses only)

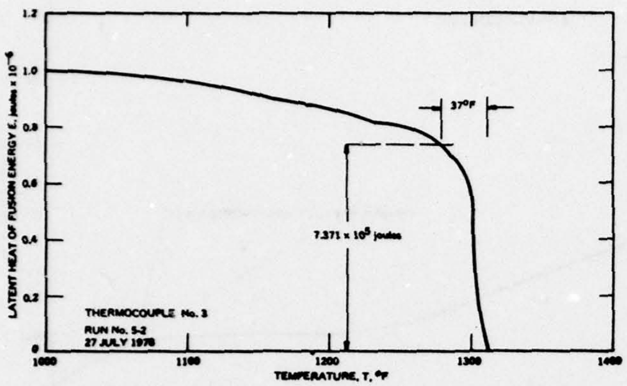


Figure 23. Latent Heat Release During Discharge (Thermal Losses only)

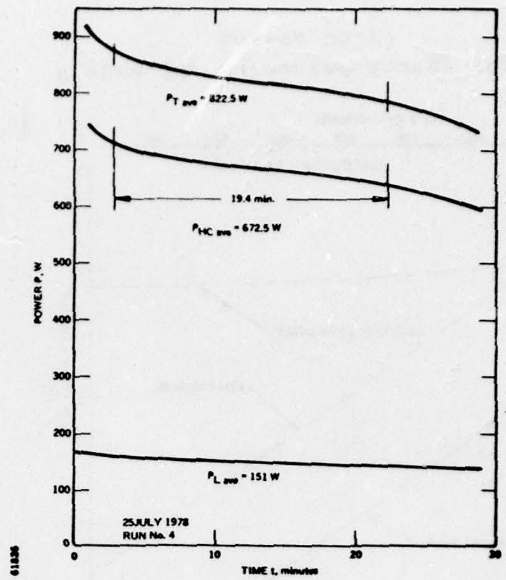


Figure 24. Power Dissipation Distribution During Discharge (Radiation & Forced Convection with Air @ $\dot{W}$=0.67 g/sec)

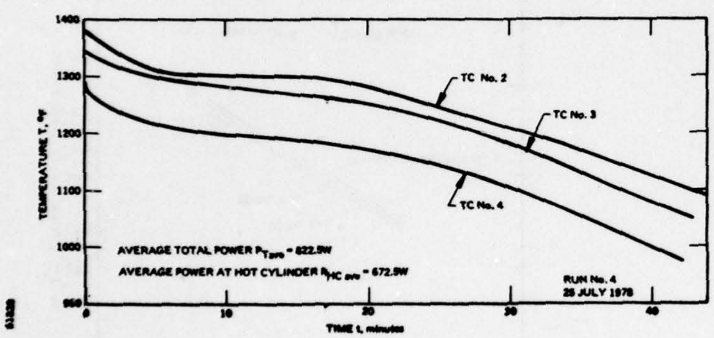


Figure 25. Temperatures During Discharge (Radiation & Forced Convection with Air @ $\dot{W}$=0.67 g/sec)

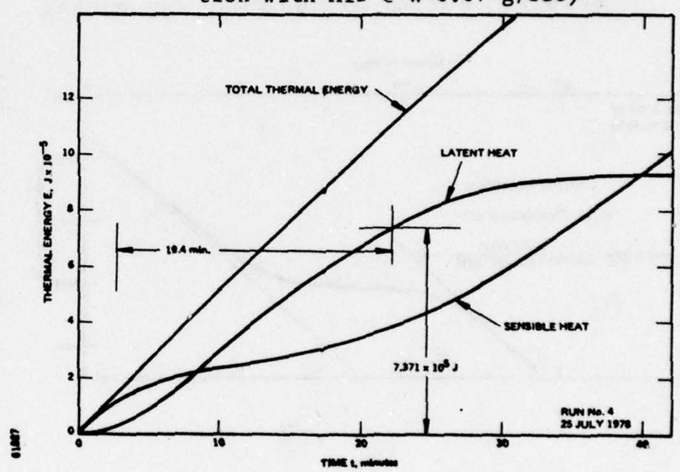


Figure 26. Thermal Energy Distribution During Discharge (Radiation & Forced Convection with Air @ $\dot{W}$=0.67 g/sec)

At the temperature at which the electrical power was turned off, the thermal losses, P_L, were 175.6W resulting in a charging rate of P_{TES} = 378.9W. At this rate the temperature should increase by 6.71^{o}F/minute. From Figure 28 it can be seen that the temperature changed only at a rate of 3.01^{o}F/minute indicating that energy was still being absorbed in the thermal storage material as latent heat of fusion.

The incomplete charging of the TES unit becomes also obvious from the discharge rate at the beginning of the discharge cycle. If the TES loses energy only by thermal losses, the rate of temperature drop at the beginning of the discharge cycle is a function of the temperature. At a temperature of 1340^{o}F, the indicated temperature of thermocouple #3 should decrease by 2.96^{o}F/minute. The actual rate at which the temperature decreased was 5.46^{o}F/minute as shown in Figure 28. This indicated that when the external power input was stopped, sensible heat was absorbed as latent heat of fusion by the TES material. When the TES unit was charged with a power input of P_{in} = 437W, the temperature as indicated by thermocouple #3 had to reach 1380^{o}F in order for the rate of temperature increase to approach the rate which indicates that all absorbed energy is being stored as sensible heat in the TES unit and that no longer melting takes place. This is shown in Figure 20.

The effect of charging rate on the temperature at which the latent heat of the thermal energy storage material is being stored can be seen in Figure 29.

The dependence of the temperature of the TES unit at the end of the charging cycle on the charging rate indicates that the heat transfer from the molten material to the solid material is not infinite. A finite heat transfer film coefficient exists which might be a function of gravity. Thus, a temperature differential must be generated between the molten material and the material which is still in its solid state to affect the heat flux required for melting.

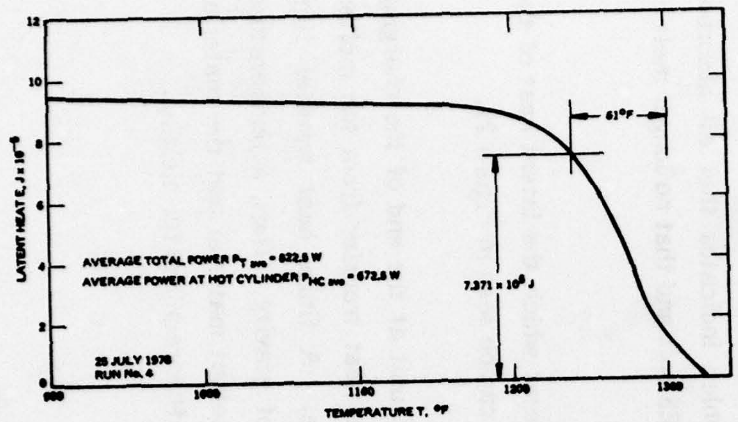


Figure 27. Latent Heat Release During Discharge (Radiation & Forced Convection with Air @ $\dot{W}$=0.67 g/sec)

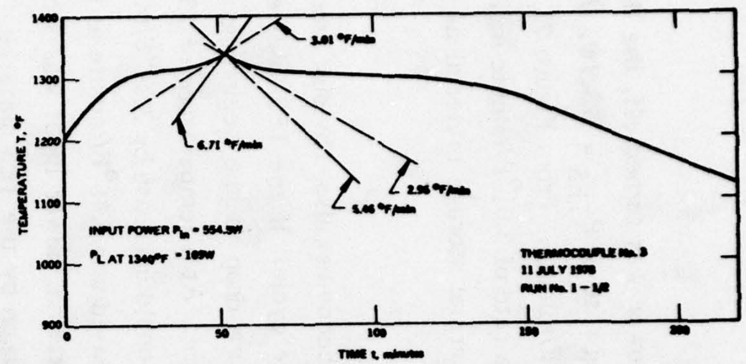


Figure 28. Temperature During Charging and Discharge

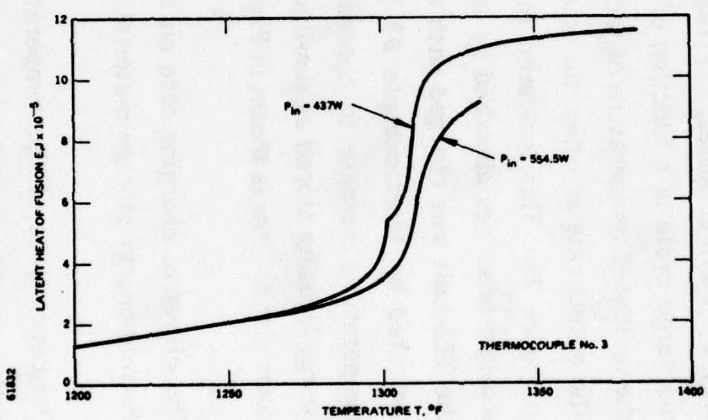


Figure 29. Effect of Charging Rate on Latent Heat Absorption

SECTION V

CONCLUSIONS

The objective of this additional task to the Thermal Energy Storage Demonstration Unit program was the improvement of the Hi-Cap Cryogenic Cooler Thermal Energy Storage Unit, the fabrication of a second Hi-Cap TES unit and the functional testing of the unit. All changes in the original design proved out to be improvements. The modification in the insulation resulted in the desired decrease of the thermal losses by 8W. With the added conduction barrier between the radiation heat shield and the mounting flange, the goal of limiting the thermal losses through the insulation to only 5 percent of the Hi-Cap cryogenic cooler hot cylinder power requirement at the nominal operating temperature of 1250°F has now been achieved. The test data indicate that the second Hi-Cap TES unit essentially demonstrates the same performance as the first Hi-Cap TES unit.

The instrumentation consisting of the three 1/16-inch diameter Inconel sheathed K calibration thermocouples performed well and consistently. The modification of the hot cylinder, flange and terminal ring improved the fabrication of the device considerably without any detrimental effects on the performance of the TES unit.

☆U.S.Government Printing Office: 1979 — 657-002/540